REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0344

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
02-JUL-2003

3. REPORT TYPE AND DATES COVERED
FINAL (15-SEP-2002 TO 14-JAN-2003)

4. TITLE AND SUBTITLE
~~AFOSR WORKSHOP ON MULTIFUNCTINAL AND HYBRIDIZED AEROSPACE MATERIALS AND STRUCTURES~~

5. FUNDING NUMBERS
F49620-02-1-0432

6. AUTHOR(S)

PROFESSOR C. T. SUN

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
PURDUE UNIVERSITY
SPONSORED PROGRAM SERVICES
610 PURDUE MALL
WEST LAFAYETTE, IN

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
4015 WILSON BOULEVARD
ARLINGTON, VA 22203

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

20040709 019

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVED FOR PUPLIC RELEASE, DISTRIBUTION IS UNLIMITED

13. ABSTRACT *(Maximum 200 words)*

The "Microstructure Testing and Analysis Laboratory" is a new facility for the mechanical testing of small specimens, soft material, and small structures. The main components of the laboratory are a low force electrodynamically actuated test frame for axial/torsion and combined loading, a digital image correlation system for the measurement of displacement fields, and a stereovision system for investigations of fracture surface

The facilities have been used successfully in research projects on carbon-carbon composites, and in investigations of porous polymeric materials, as well as for projects in a graduate course on "Micromechanics of Materials." In all experiments performed so far the experimental facilities have performed satisfactory.

14. SUBJECT TERMS

15. NUMBER OF PAGES
175

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFED	UNCLASSIFIED	

10/20/03

38 ATTENDEES:
26 Speakers, Panelists & Discussion Leaders;
1 Moderator; 1 Organizer;
10 Invited Guests

MODERATOR:
*C. T. Sun (**Purdue U**)

OPENING REMARK:
01 Les Lee (**AFOSR**) “AFOSR Perspective”

<u>Background Overview</u> *(2:30 - 4:00 PM, 23 October 2002; Stewart Center Room 214C)*

KEYNOTE SPEAKERS:
15 min. presentation & 5 min. question per each
02 Brian Sanders (**AFRL/VA**) "Overview of Research at AFRL Air Vehicles Directorate"
03 David Banks (**Boeing Phantom Works**) "Overview of Multifunctional Structures Research"
04 Steve Donaldson (**AFRL/ML**) "Overview of Research at AFRL Materials Directorate "
05 Jeff Welsh (**AFRL/VS**) "Overview of Research at AFRL Space Vehicles Directorate "

1st AIR FORCE WORKSHOP ON "MULTIFUNCTIONAL AEROSPACE MATERIALS"

October 23-24, 2002, Purdue University, W. Lafayette, IN

(Immediately following the 17th Technical Conference of American Society for Composites)

ORGANIZING COMMITTEE:

Les Lee (AFOSR), *Chair*
Steve Donaldson (AFRL/ML)
Tom Hahn (UCLA)
Brian Sanders (AFRL/VA)
C. T. Sun (Purdue U)

<u>Multifunctional Design</u> *(4:00 - 6:00 PM, 23 October 2002; Stewart Center Room 214C)*

*DISCUSSION LEADER: Bill Baron (**AFRL/VA**)*

KEYNOTE SPEAKERS:

15 min. presentation

[06] Bill Baron (**AFRL/VA**) "Conformal Load Bearing Antenna Structures"
[07] Barton Bennett (**Odyssian**) "Multifunctional Structures with Embedded Subsystem Functionality"
[08] Jim Thomas (**NRL**) "Design Issues for Multifunctional Materials and Structures"

PANELISTS *(Expertise)*:

10 min. comments or alternative opinion per each

[09] Jim Mason (**Notre Dame U**) "Circuit Integration and Thermal Management"
[10] Greg Schoeppner (**AFRL/ML**) "Design Issues for Multifunctional Composites"
[11] David Banks (**Boeing Phantom Works**) "Health Monitoring of Multifunctional Structures"

OPEN DISCUSSION: *45 min*

(DINNER SERVED)

Self-Diagnosis *(8:00 - 10:00 AM, 24 October 2002; Stewart Center Room 313)*

*DISCUSSION LEADER: Munir Sindir (***Boeing Rocketdyne***)*

KEYNOTE SPEAKERS:

15 min. presentation per each

[12] Munir Sindir (**Boeing Rocketdyne**) "Health Management System Needs - Space Transportation Perspective"

[13] Mark Derriso (**AFRL/VA**) "Structural Health Monitoring"

[14] David Green (**Physical Sciences**) "Materials That Sense Their Environment"

PANELISTS *(Expertise)*:

10 min. comments or alternative opinion per each

[15] Bill Curtin (**Brown U**) "Self-diagnosis of Damage in CFRP by Electrical Resistance"

[16] Fu-Kuo Chang (**Stanford U**) "Demand and Challenges in Structural Health Monitoring"

[17] Alex Bogdanovich (**3Tex**) "3-D Woven Composite Structures with Integrated Fiber Optic Sensors"

[18] Steve Kreger (**Blue Road Research**) "Multi-axis Fiber Grating Strain Sensors"

OPEN DISCUSSION: *45 min*

Self-Cooling *(10:15 AM - 12:25 PM, 24 October 2002; Stewart Center Room 313)*

*DISCUSSION LEADER: Roger Morgan (**Texas A&M U**)*

KEYNOTE SPEAKERS:

15 min. presentation

[19] David Brown (**AFRL/VA**) "Thermal Protection Systems"
[20] Keith Bowman (**AFRL/ML**) "Thermal Management Issues and Program Directions"
[21] Roger Morgan (**Texas A&M U**) "Self Fast Cooling Mechanisms"

PANELISTS (*Expertise*):

10 min. comments or alternative opinion per each

[22] Patrick Kwon (**Michigan State U**) "Micro Heat Exchanger"
[23] Jim Sutter (**NASA Lewis**) "Thermal Management and High Temperature Polymers"
[24] Khalid Lafdi (**AFRL/ML**) "Graphite Foams as Heat Carrier for Thermal Control"

OPEN DISCUSSION: *45 min*

(LUNCHEON SERVED)

****

SPECIAL GUESTS *INVITED*:

Jaycee Chung (**Global Contour**)
Krishna Jonnalagadda (**Motorola**)
Doug Adams (**Purdue U**)
Tom Farris (**Purdue U**)
Hyonny Kim (**Purdue U**)
Thomas Siegmund (**Purdue U**)
John Starkovich (**TRW**)
Stephen Hallett (**U Bristol, UK**)
Brian Rice (**U Dayton**)
Philippe Geubelle (**U Illinois**)

MECHANICS OF MATERIALS AND DEVICES: AFOSR PERSPECTIVE

B. L. ("Les") Lee

Program Manager

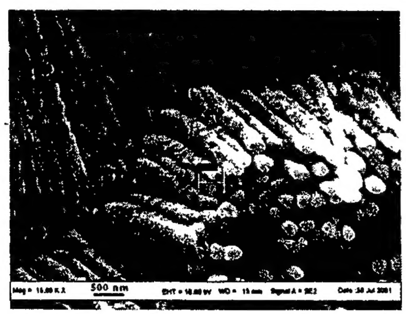
Mechanics of Materials & Devices

Air Force Office of Scientific Research

MISSION

Establish the science base for *integration* of *advanced materials* and *devices* into future Air Force systems.

Materials/Devices



Processing/
Manufacture

Mechanics
of Materials
& Devices

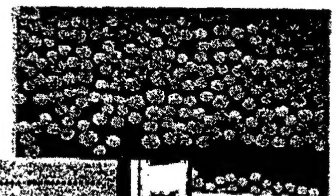
Design

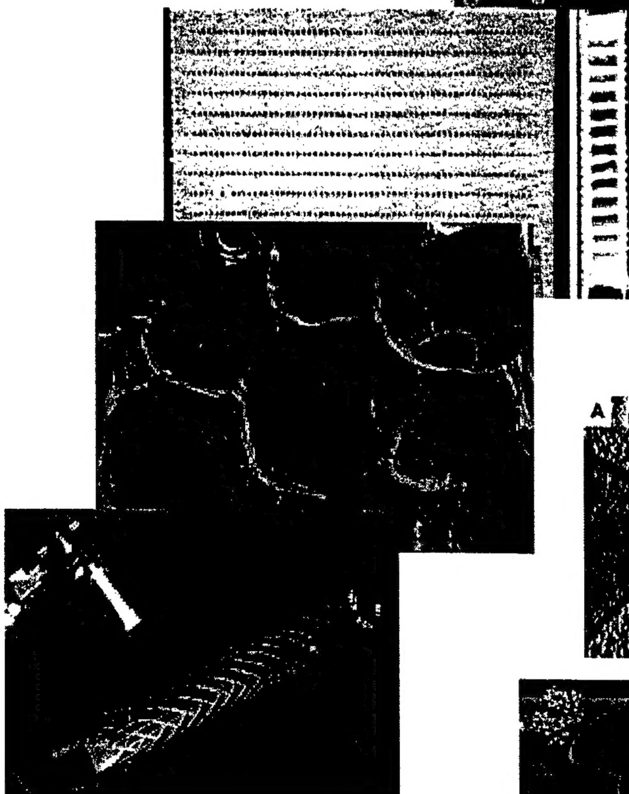
Structures

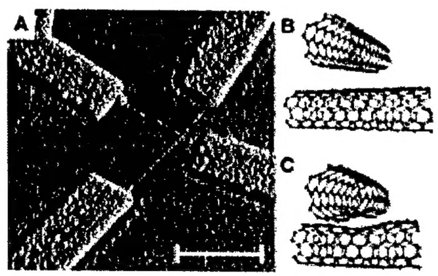
Properties

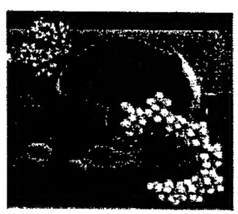
Performance

MECHANICS ISSUES IN
Design, Manufacturing & Sustainability:









**Advanced Fiber Composites*
Stealthy Materials
High-Performance Metals

**Structural Ceramic Composites*
Propellants: particulate composites
**Carbon Foam*
Shape-Memory Alloy
Functionally Graded Materials

**Multifunction Composites*
**Nano-materials*
Self-Diagnosing Structures
**Self-Healing Materials*

Adhesives & Joints

Sensors
Micro-devices incl. MEMS
Nano-devices

THRUST AREAS vs. STRATEGIC RESEARCH AREAS

THRUST AREAS -

Thrust Areas		Strategic Research Areas
		Nano-materials 2
Affordable Processing		*Multifunctional Behavor:*
Vibration Mitigation 1 (*Materials Aspects*)		*Multifunction Materials* 1 *Micro- & Nano-devices* 1
Durability	→	*Self-Diagnosis* 1
Damage Tolerance	→	*Self-Healing* 1,3
Micromechanics	→	*Multi-scale Model*
Life Prediction	→	*Life Extension*

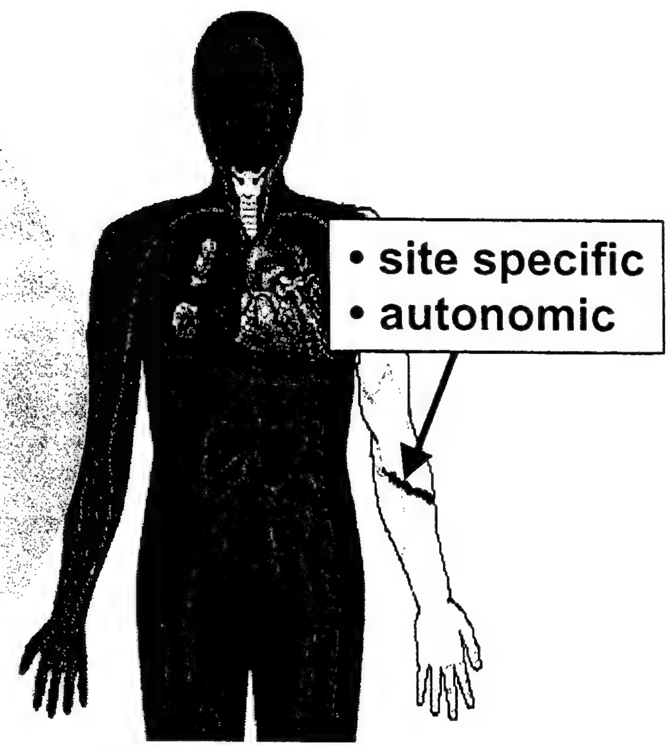
1 *Smart Materials/Structures - SRA*
2 *Nano Science - SRA*
3 *Biomimetics - SRA*

VISION

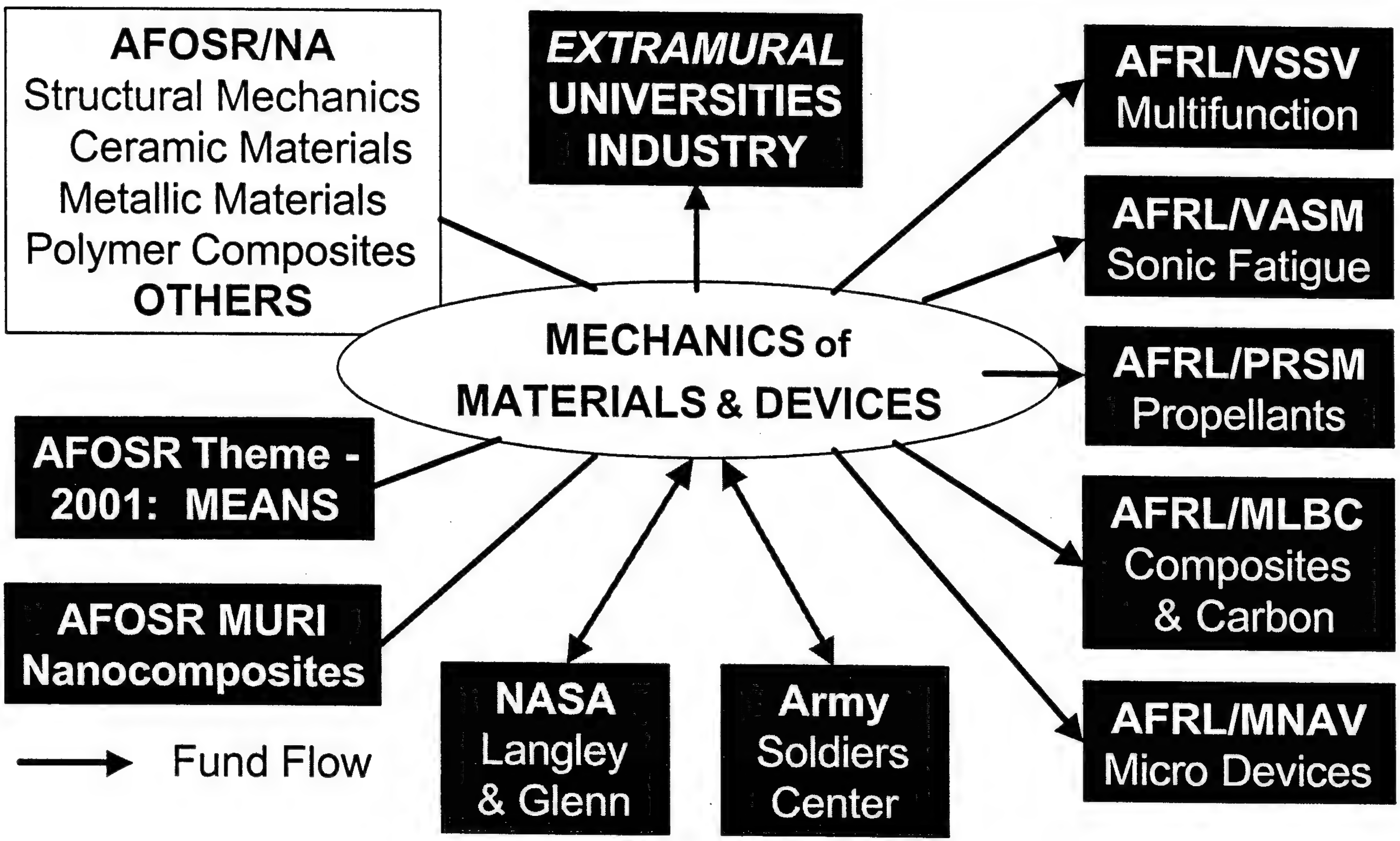
- Biomimetics
- Design for Coupled Multi-functionality
- Nano-materials
- Concurrent Multi-scale Model
- Micro- & Nano-Devices
- Manufacturing Sci
- Neural Network & Information Sci

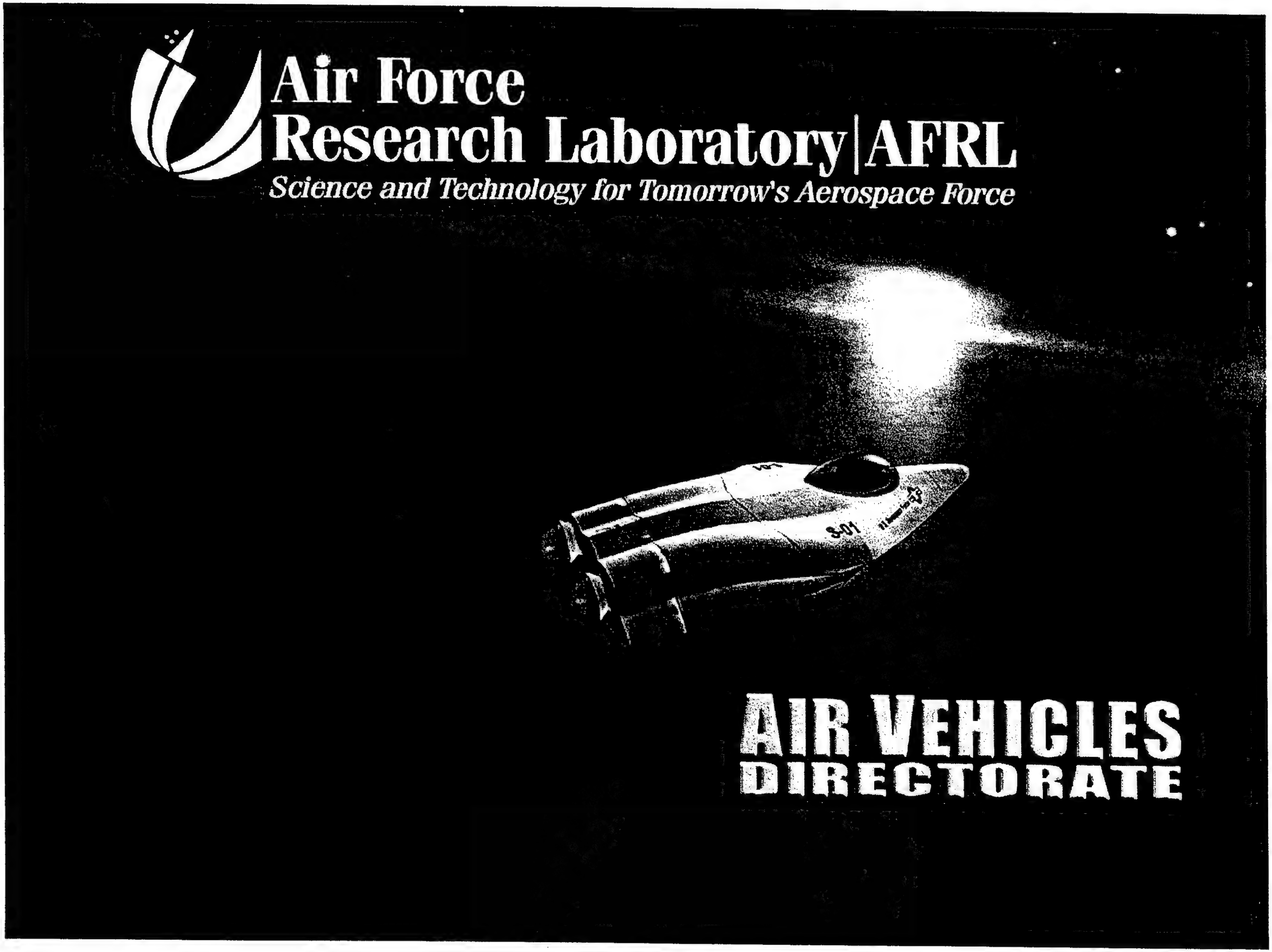
AUTONOMIC
AEROSPACE
STRUCTURES

- Self-Diagnosis
- Self-Healing
- Threat Neutralization
- Self-Cooling



PROGRAM INTERACTION

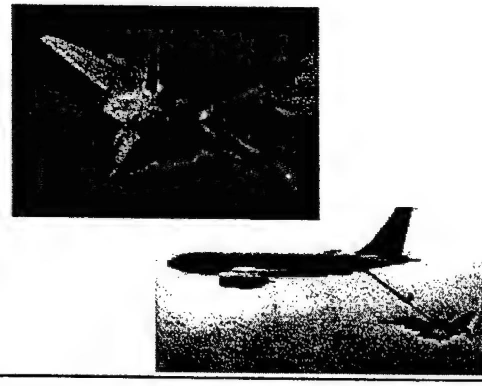



Air Force
Research Laboratory|AFRL
Science and Technology for Tomorrow's Aerospace Force
S-01
AIR VEHICLES
DIRECTORATE

AIR VEHICLES DIRECTORATE
S&T Focus Areas

Sustainment:

Technology insertion to enable today's fleet to meet tomorrow's warfighter needs

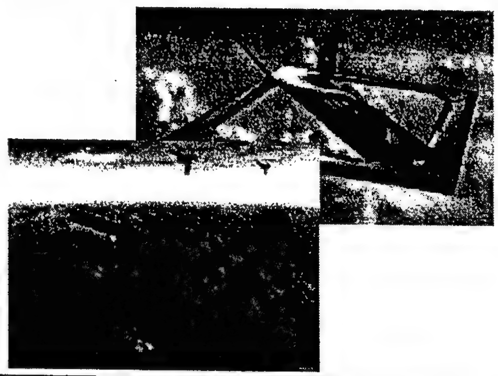


Increased mission capable rates

Reduced operation and support costs

Unmanned Air Vehicles:

Technologies to enable routine operation of high payoff UAV alternatives across the full spectrum of warfare



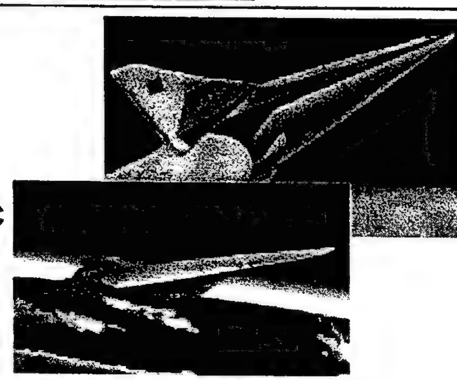
Seamless manned / unmanned vehicle operation

Superior mission capability at reduced cost

Intelligent control of UAV swarms

Space Access & Future Strike Technology:

Affordable space access and quick reaction trans-atmospheric capability



Aircraft like operation -- quick turnaround and flexible mission capability

Global engagement in less than 3 hours

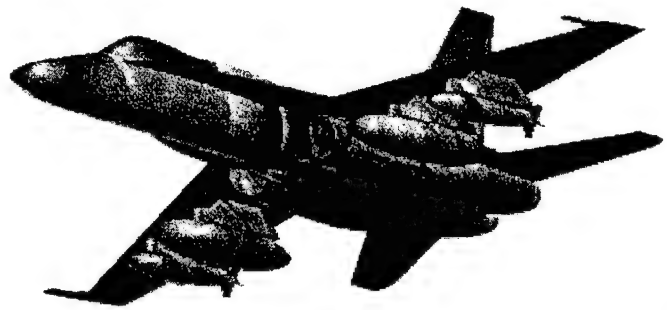
Reduced cost for access to space

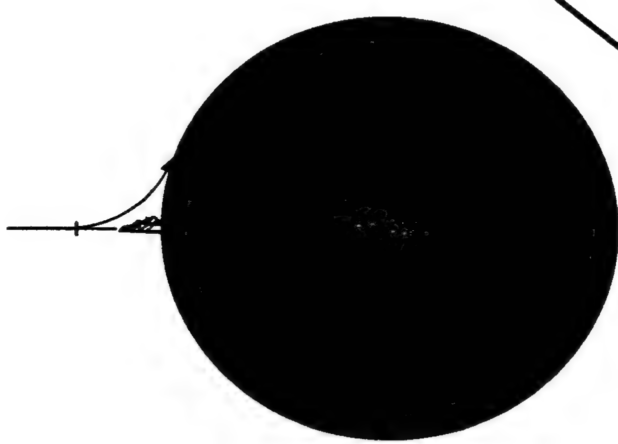
EXPERIMENTAL FACILITIES

- Combined Environment Acoustic Chamber
  - Simulates severe aeroacoustic and engine environments
  - Only facility capable of achieving 173dB and 2500°F on a 9’x4’ specimen

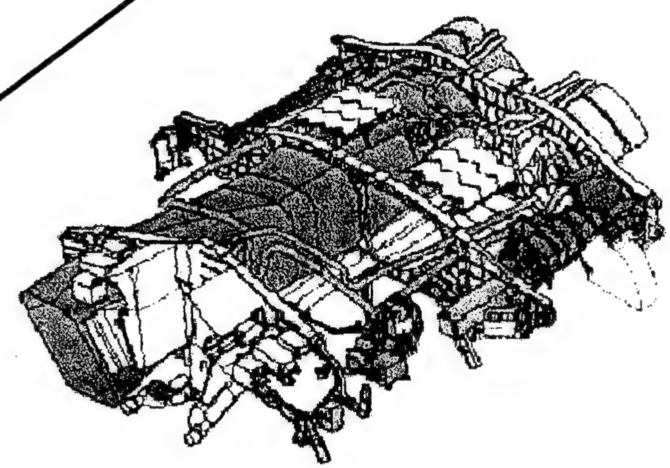
CENTERS OF EXCELLENCE

Computational Science





Control Science



Multi-Disciplinary Technologies

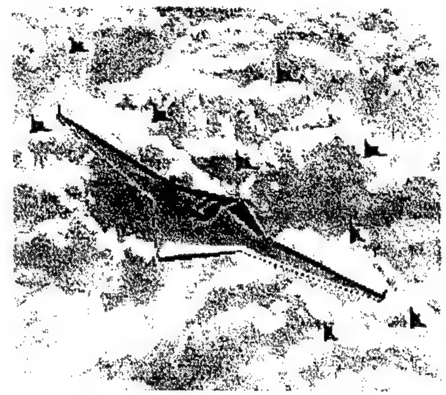
STRUCTURES DIVISION
STRUCTURAL DESIGN AND DEVELOPMENT BRANCH

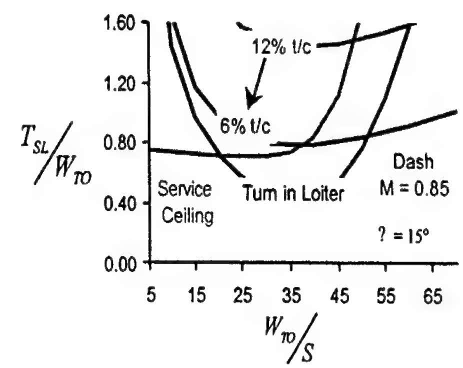
MULTIFUNCTIONAL & ADAPTIVE STRUCTURES TEAM (MAST)

AFRL	External Collaborators
Baron, Bowman, Forster, Garner, Joo, Keihl, Reich, Sanders, Cannon (VACC)	Washington, Ohio State University
	Weisshaar/ Crossley, Purdue
	Murray, Univ of Dayton
	Inman, VPI
	Alton, Univ of Dayton

SCOPE OF PROGRAM

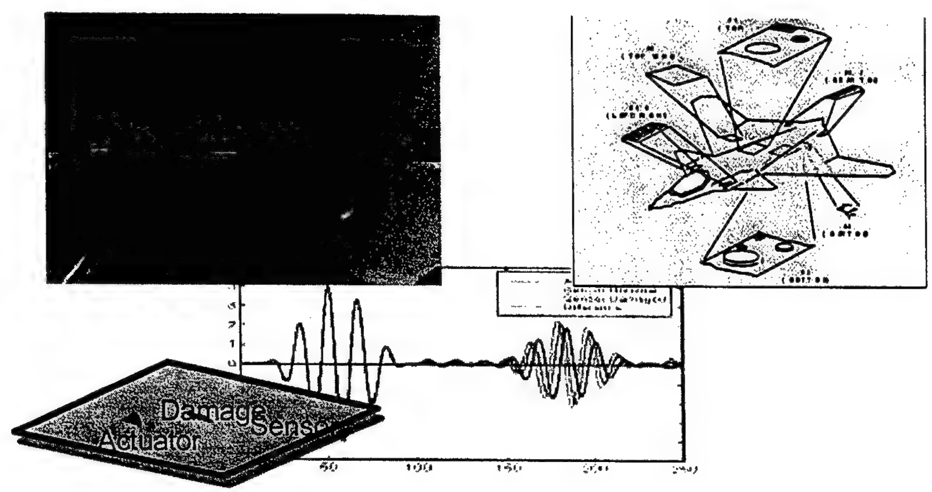
Mission Identification
&
Vehicle Configuration





Integrated Structures

- •Shape Control
- •Antenna Integration
- •Energy Storage & Harvesting

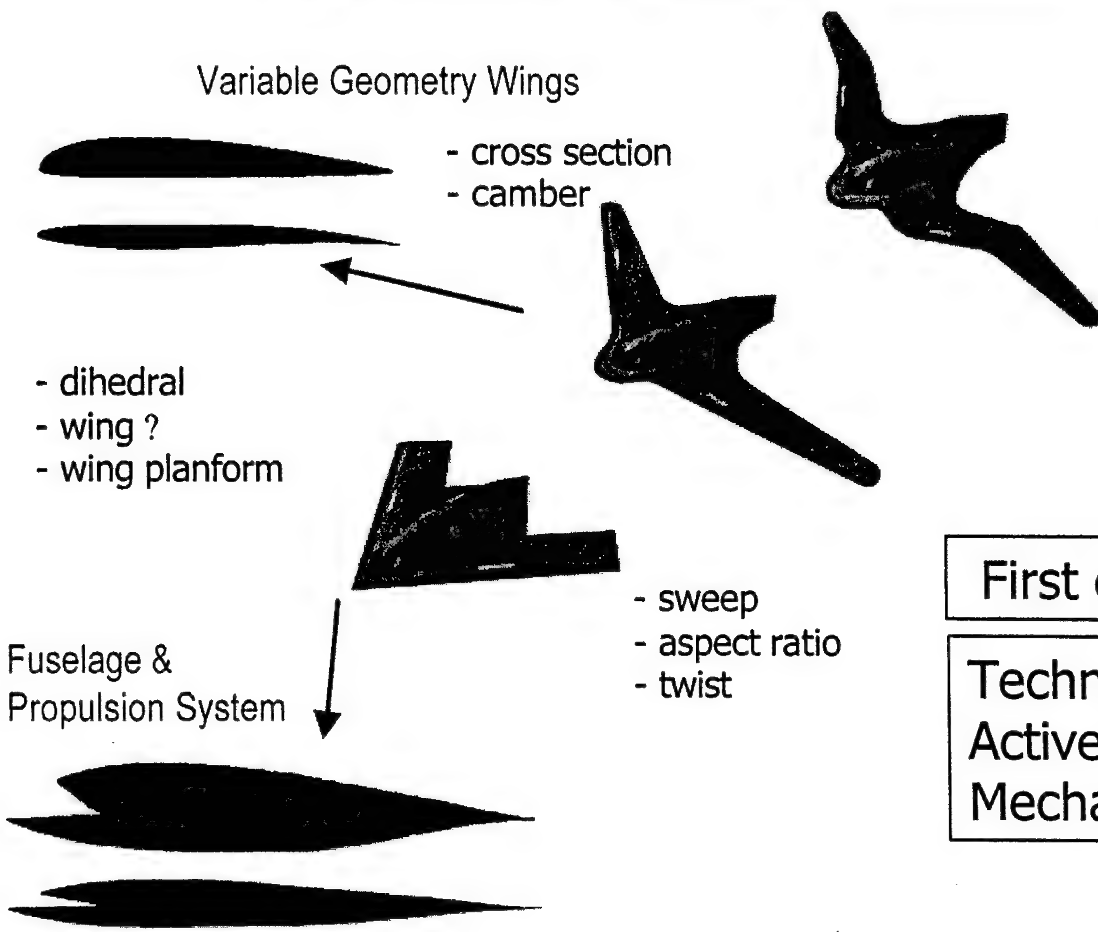


Energy Based Design

$$Exergy\ ?\ (u ? u_o) ? T_o(s ? s_o) ? \frac{P_o}{J}(? ? ?_o) ? \frac{V^2}{2gJ} ? \frac{g}{g_c J}(z ? z_o) ? ?_c\ (? ? ?_o)N_c ?$$

DARPA/AF
MORPHING AIRCRAFT PROGRAM

- From rigid airframes to commanded, time variant, variable geometry, load-bearing structures



Aircraft are currently designed around specific missions

Can we develop aircraft capable of multiple missions?
- e.g., reconnaissance air vehicles transform into effective ground attack vehicles

First challenge: Morph the wing

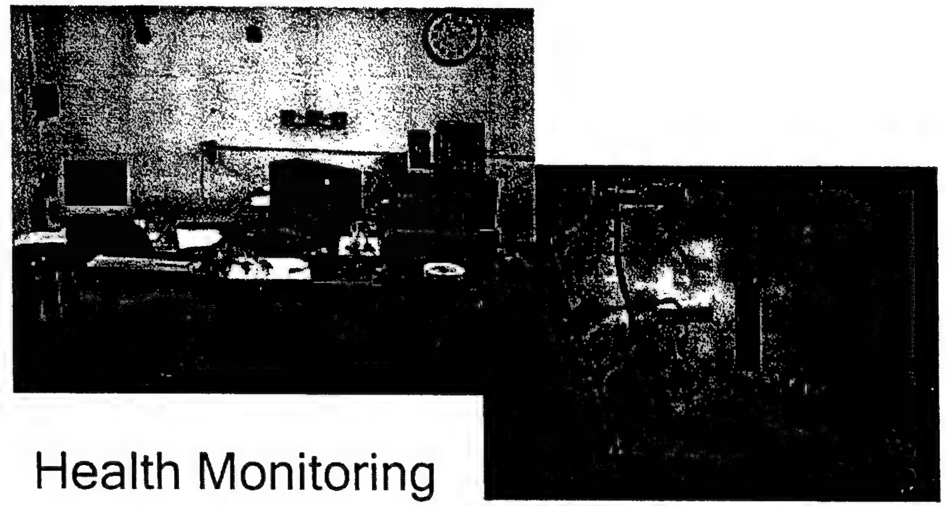
Technology Challenges:
Active Skins
Mechanism Design & Integration

Multifunctional Structures Laboratory

Objective

Have the capability to conduct experimental research and rapidly evaluate sensor and actuator technology for application to MFS

Located in Bldg 65



Health Monitoring

Shape Control

1st Air Force Workshop on "Multifunctional Aerospace Material"

Overview of Multifunctional Structures R&D at Boeing

Dave Banks

Boeing Phantom Works

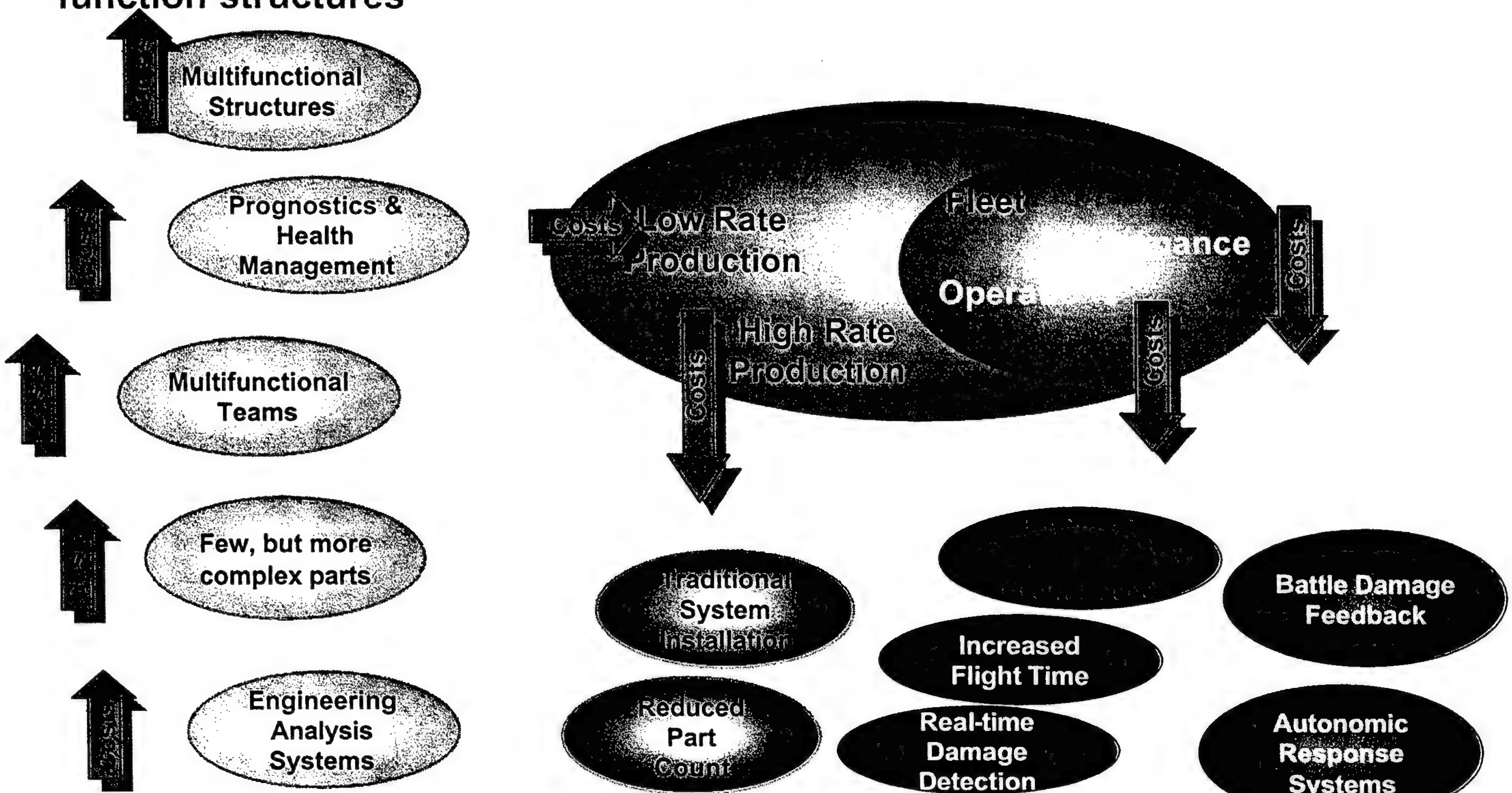
David.L.Banks@Boeing.Com
206-655-3855

Some Definitions

- **Any structure with functions beyond load carrying capabilities**
- **Possible integration features:**
  - Integrated attachments for other systems
  - Conduits (for air, fuel venting, or other fluids)
  - Energy Absorption (for vibration and acoustic noise suppression)
  - Thermal Control (cooling and heating)
  - Electrical Systems & Conductive Structures (for grounding and lightning)
  - Actuation (for aerodynamic control, fluid movement
  - Sensing (pressure, acceleration, acoustic, strain, temperature, Corrosion…)
  - Optics (for data or for light transmission)
  - Energy Generation (remote sensors & vibration suppression)
  - Self-healing structures / self-repairing structures

Benefits

Multifunctional Structures Cost More ...than single-function structures → **System Level Integration & Life cycle Costs are Lower**



Multifunctional Structures Systems / Technology Development Matrix

Multifunctional Systems	Fiber Optic Sensors	Fiber Optic Data Bus	Improved Ultrasonic Fuel Sensor	Flex Circuits	Signal Bus Hi/Low BW	Power Bus	Integrated Piezo Actuators	Integrated MEMS Strain Sensors	Sensor Data Processing Algorithms	Structurally Integrated Connectors (wire & FO)	Structural Inter-connects	Flat Wire through Spar/Skin Joint	Analysis Models / Tools
Integrated Cabling	X	X		X	X	X	X			X	X	X	X
Fuel Monitoring			X	X	X	X			X	X		X	
Structural Health Monitoring	X			X	X	X	X	X	X	X	X	X	X
Demonstration Test System			X	X	X	X	X		X	X	X	X	X
Planarity Compensation	X								X	X		X	X
Structural Test	X			X	X	X	X	X	X	X	X	X	X
Integrated Manufacturing Sensors	X			X	X		X	X	X	X	X	X	X
Lightning				X		X				X	X		
Structurally Integrated Apertures	X	X	X	X	X	X	X		X	X	X	X	X
Active Rotor Blade	X	X		X	X	X	X		X	X	X	X	X

TRL 1-3 | TRL 3-4 | TRL 5-7 | TRL 8-10

Organic Matrix Composites Research Activities at AFRL/MLBC

Steven L. Donaldson

Materials & Manufacturing Directorate

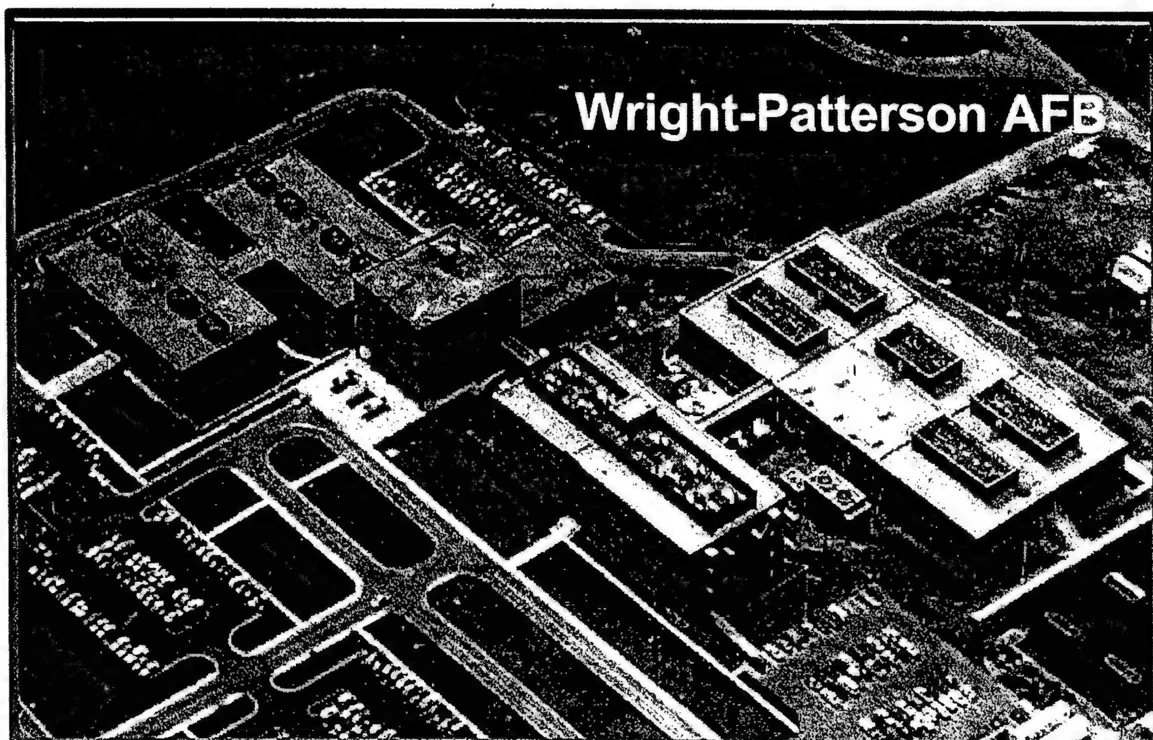
Air Force Research Laboratory

ML Mission / Vision

Plan and execute the USAF program for materials and manufacturing in the areas of basic research, exploratory development, advanced development and industrial preparedness. Provide responsive support to Air Force product centers, logistics centers, and operating commands to solve system and deployment related problems and to transfer expertise.

Aerospace materials and manufacturing leadership for the Air Force and the nation.

Facilities



Materials & Manufacturing Directorate

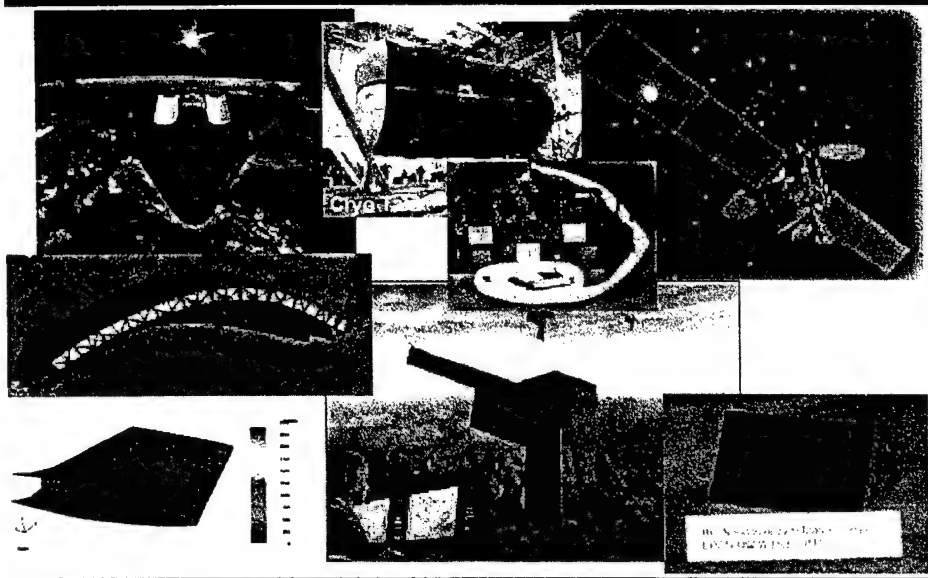
Key 21st Century Challenges for Aerospace M&P

- Maintaining "The Revolution"
- Increased Performance at an "Acceptable" Cost
- Controlling Cost With Small Production Runs
- Orchestrating Strategic Partnerships
- Reducing R&D Cycle Times Without Sacrificing Quality
- Accelerated Insertion of Materials
- Transitioning "High Risk", but "High Performance", Materials in a Risk Averse Environment

Revolutionary Opportunity Areas

- Bioengineered/Bioinspired Materials
- Nano-Tailoring
- Multi-functional Materials
- Computational Materials Science
- Atomic Engineering
- Virtual Prototyping of M&P
- Virtual Databases
- Self-inspection Capabilities/Vehicle Health Monitoring

CTA-3
Organic Matrix Composites (OMCs)



CTA DIRECTION GOALS

3.1 Develop improved, lightweight, tailored, multi-functional composite materials highly resistant to degradation in realistic severe service environments

for long range, pervasive technologies

3.2 Develop, demonstrate, and transition new and improved OMC materials, processes, and mechanics approaches for Air Force aircraft and weapons

3.3 Exploit the properties of OMCs through the development of innovative, affordable processes, material forms, and supporting repair/mechanics technologies

CTA DIRECTIONS

3.1 Advanced OMC Concepts

3.2 OMC M&P for Air Platforms

3.3 OMC M&P for Space Platforms

ACCOMPLISHMENTS

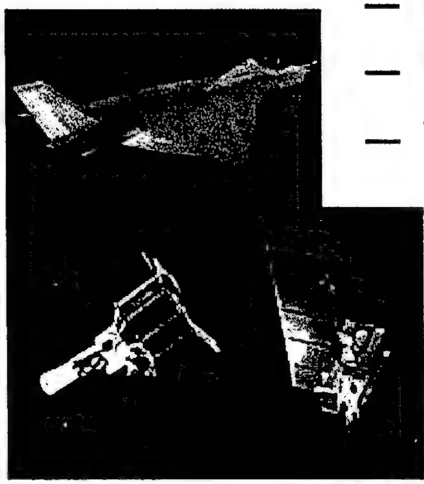
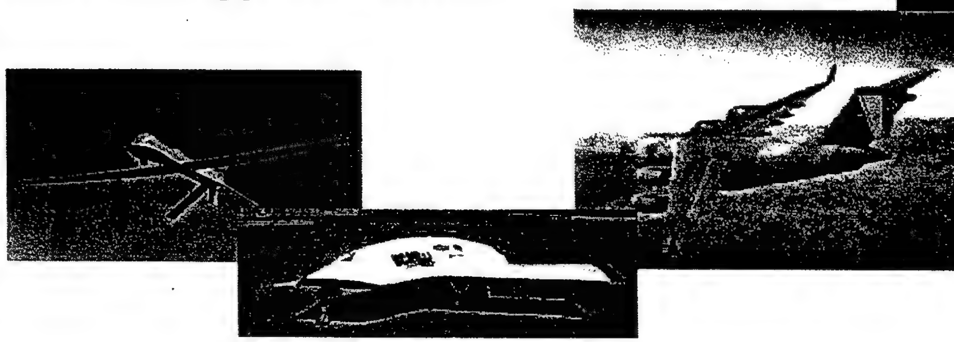
- Evaluated a new family of affordable, low recession, insulative C-C for a simulated Global Reach Trajectory (CAV application)
- Demonstrated first nanocomposite matrix advanced composite with 5% to 10% increase in laminate properties
- Demonstrated a large panel component of a low cost sandwich structure for use in JASSM and UCAV applications
- Demonstrated 40% reduction in processing time of C-C for thermal management applications
- Validated a 20% improvement in energy absorption of full scale testing of phase change enhanced aircraft brakes
- Transitioned a flow model to industry for resin transfer molding of a fighter aircraft tail section with reduced fabrication time and costs

CTA 3 OVERVIEW
Mission/Vision

Mission:

To develop, demonstrate, and transition new and improved composite materials, processes, and applicable science bases for Air Force Weapons Systems:

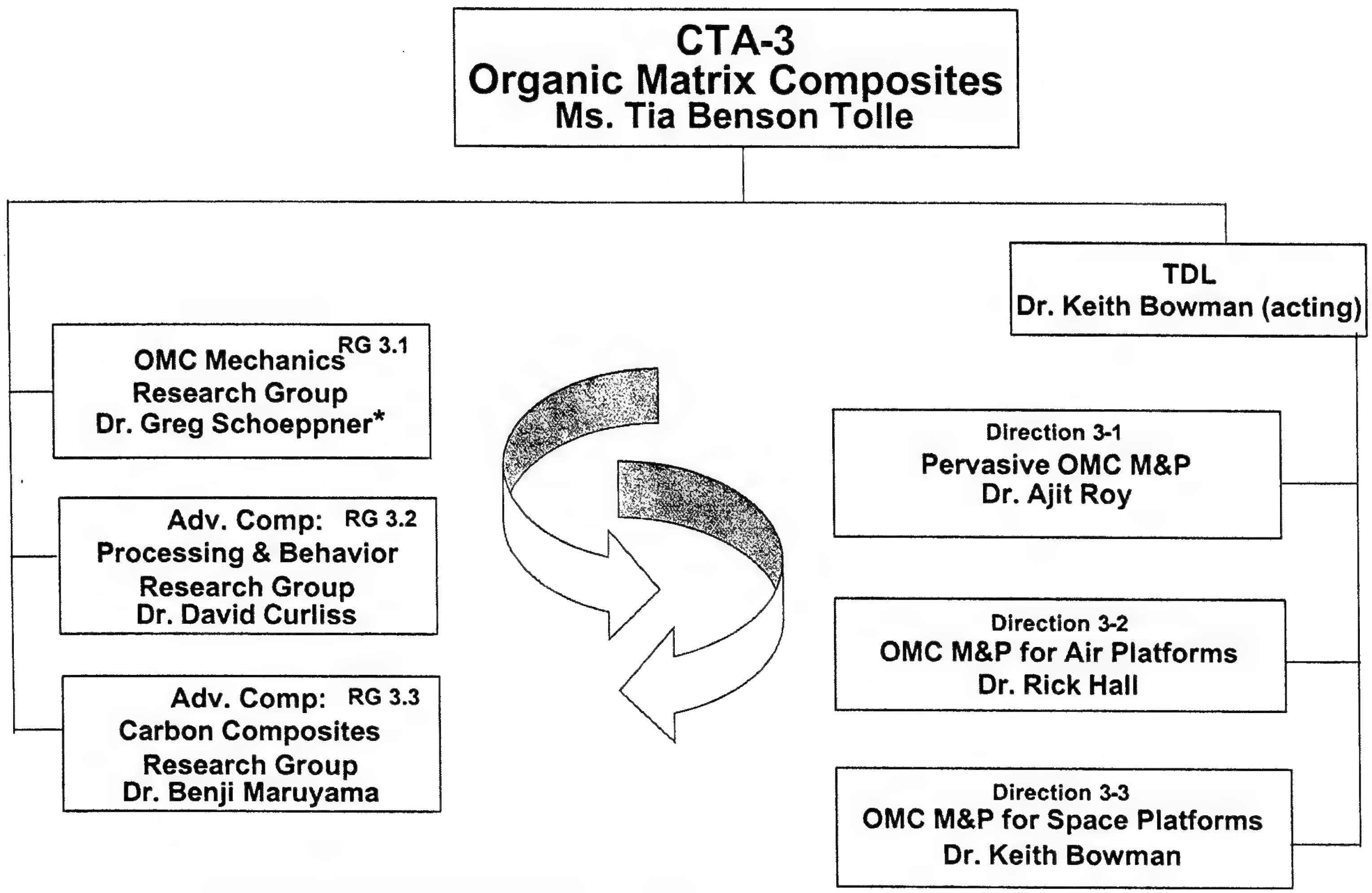
- Performance with affordability
- Improved durability and survivability
- Reduced acquisition cost and times
- Technology transition


Vision:

To develop, invest in, and implement the necessary technology for OMCs reach their full potential in affordable, flexible and mobile AF systems.

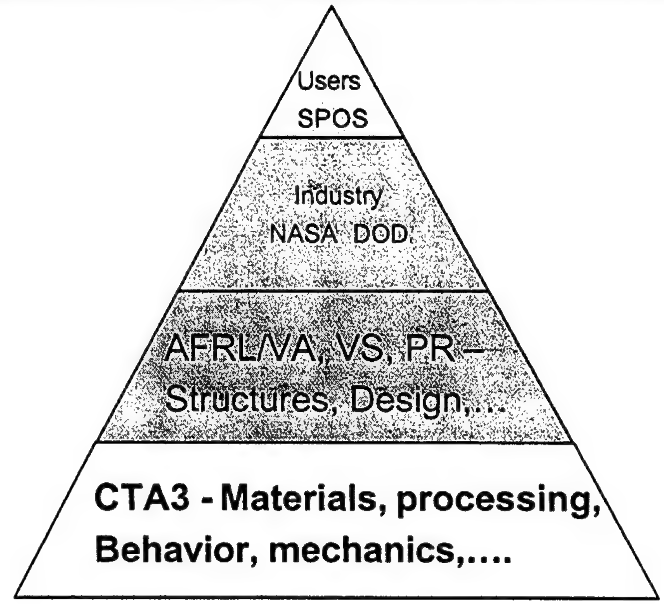
CTA-3 Organic Matrix Composites Organization



* CTA representative on ML Research Council

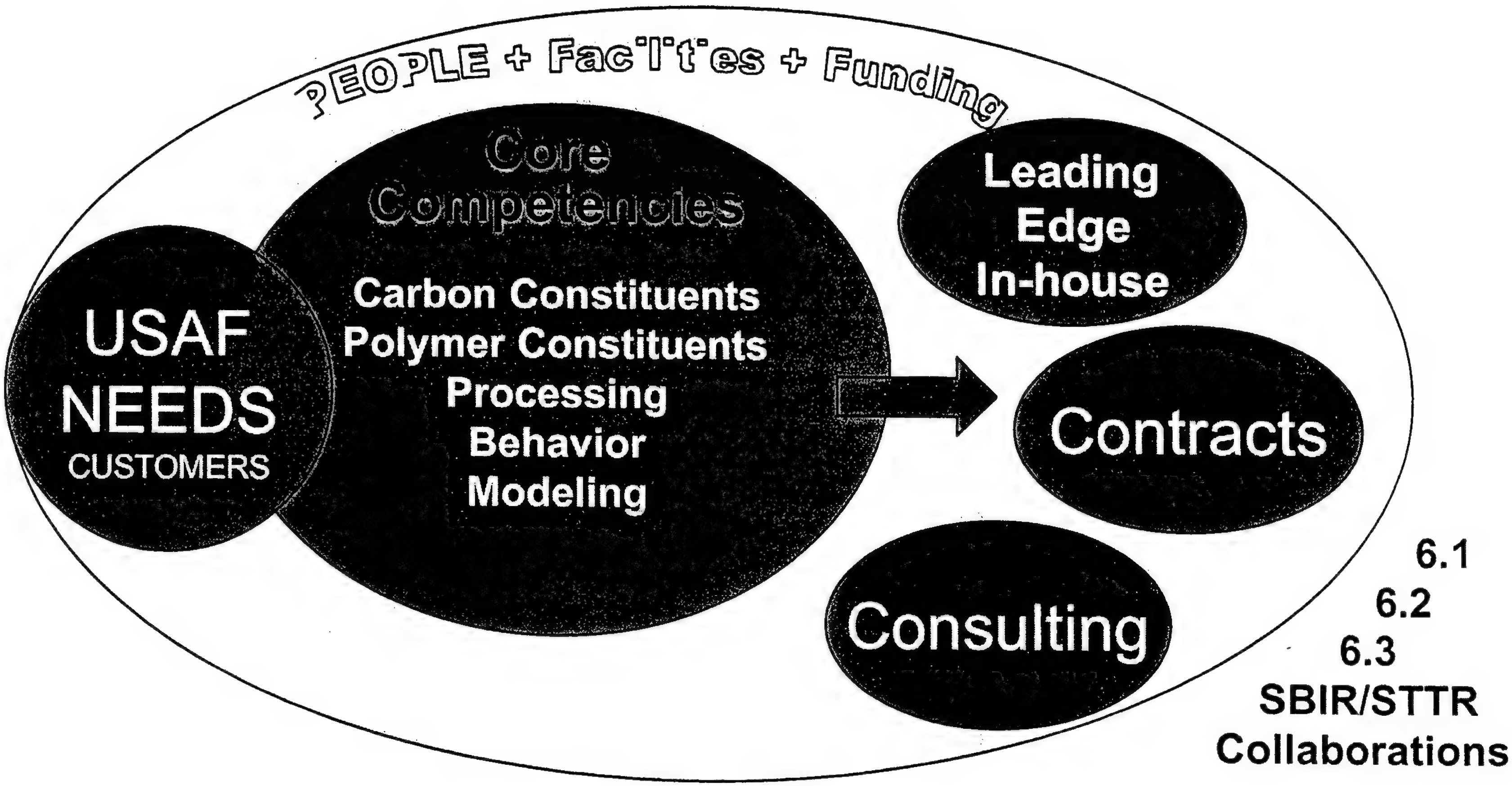
CTA 3 Niche

- ***The*** **S&T for USAF composites**
  - Integrated group - materials, processing, chemistry, mechanics, …
  - Basic research
    + customer/industry interactions
  - 6.3, 7.8/CAI ties
  - Technical Directorates



- **Technical challenges validate need**
  - F119 engine: composites replaced by Ti ($)
  - SOV: composite cryotanks, TPS: durability? compatibility?
  - ABL: chemical compatibility
  - Realize the 'why composites' – full potential

Model: What we do

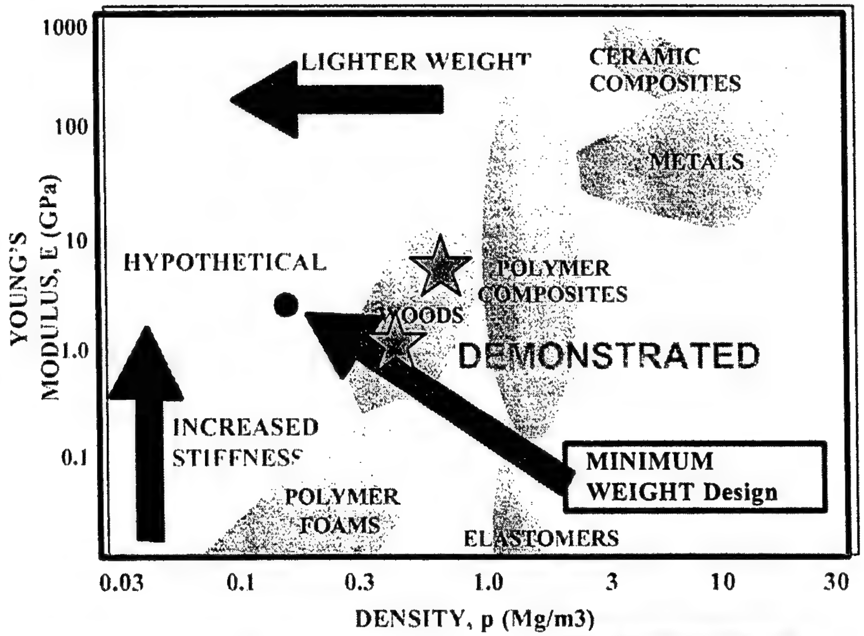


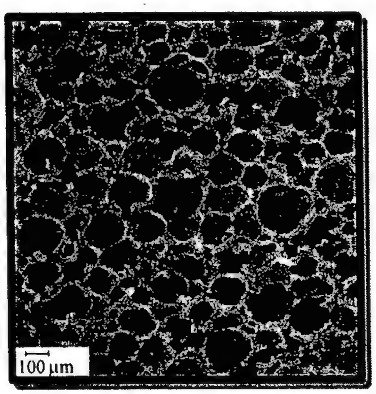
To Guide Today's Customers, Meet Future Needs, and Enable Tomorrow's Weapons Systems

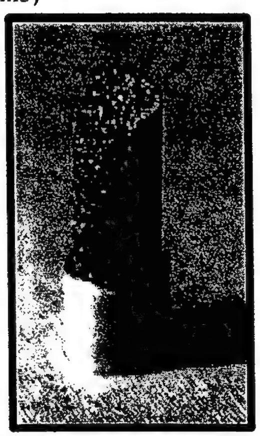
OMC Development Emphasis

- Pervasive Materials Development
  - Novel Materials Forms (Foam, Composite Preforms, NanoComposites, Bio-inspired Materials)
- Extreme Materials Environments
  - High Temperature, Cryo, LOX & GOX Compatibility
- Improved Capabilities
  - Thermal Management, Multifunctional
- Improved Understanding for Material Exploitation
  - PACT, 6.1, 6.2, Collaborations

Materials Development: Carbon Foam

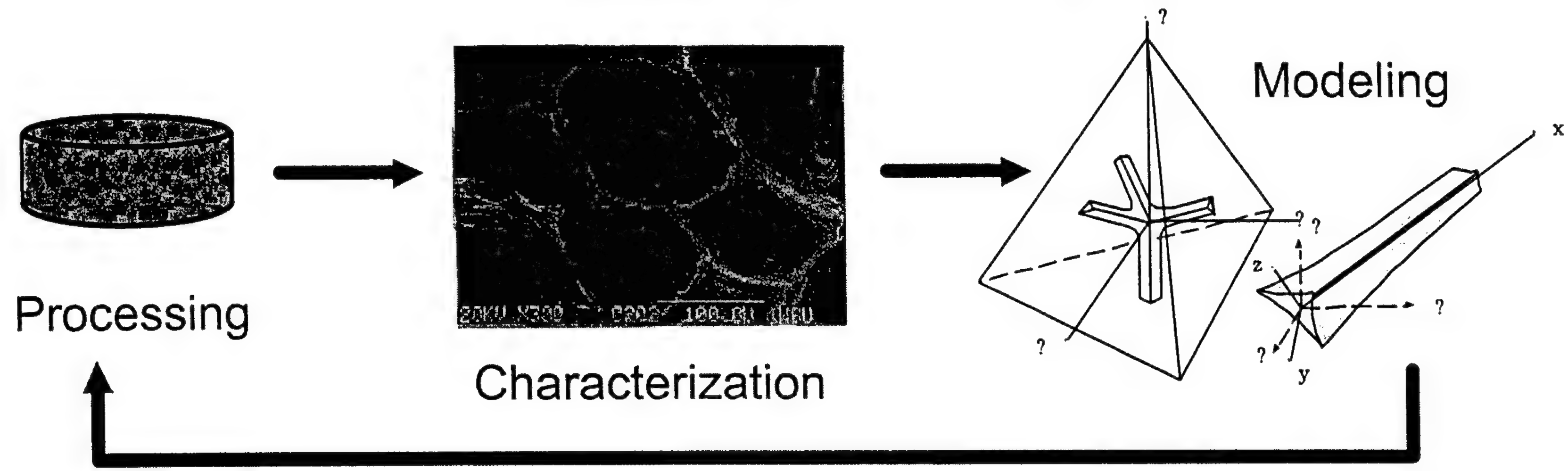






- Extremely tailorable material - process dependant
  - General qualities
    - Isotropic properties
    - Moisture insensitive
    - Ultralightweight structure
      - 3-D preform (fill with various matrices)
      - Sandwich structure
    - Wide variety of densities (5 to 50 pounds/ft^3)
  - Low temperature processing:
    - Insulator
  - High temperature processing
    - Conductor, Stronger

Carbon Foam Research Objective

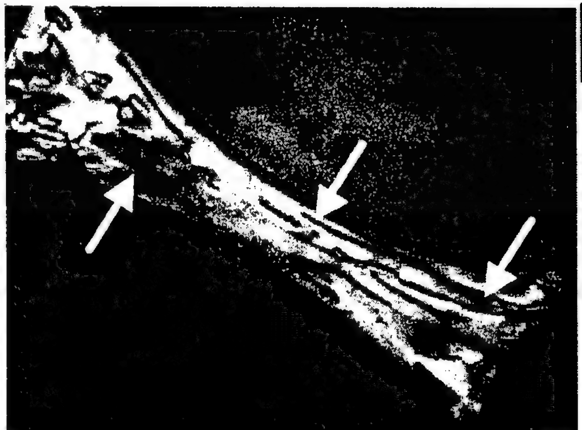


Foam ligament of about 120-150 ? m in length with changing cross-section and varying microstructure

- **Overall Objective**
  - **Integrated "Processing-Characterization-Modeling" approach to OPTIMIZE foam properties**
  - **To Model Foam Microstructure**
  - **To Characterize and Quantify Carbon Foam Ligament Microstructure**

Optical Microscopy of Stabilized Foam

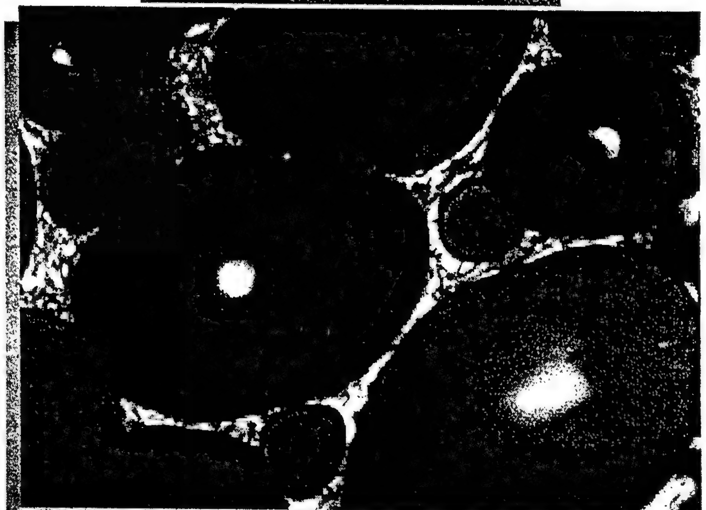
Ligaments



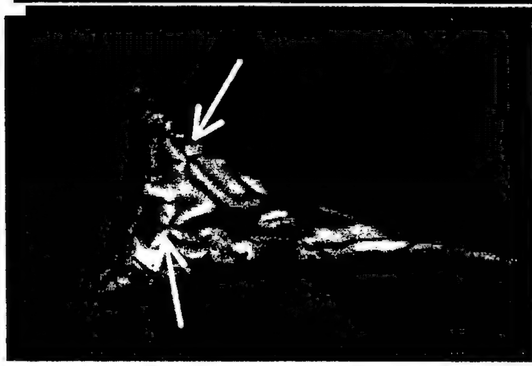
With Disclinations

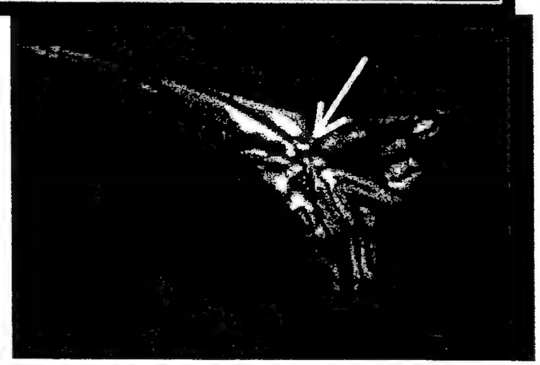
Free of Disclinations

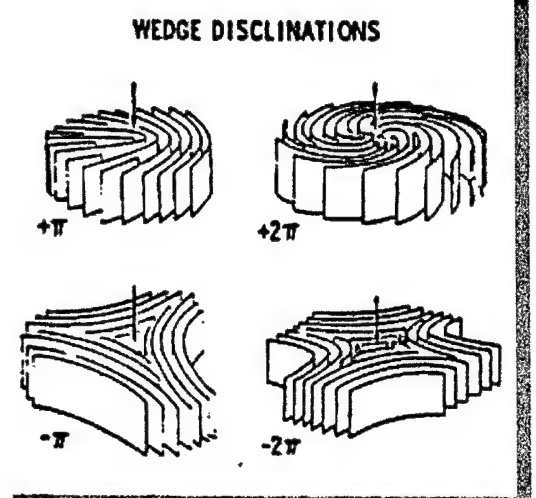
General View



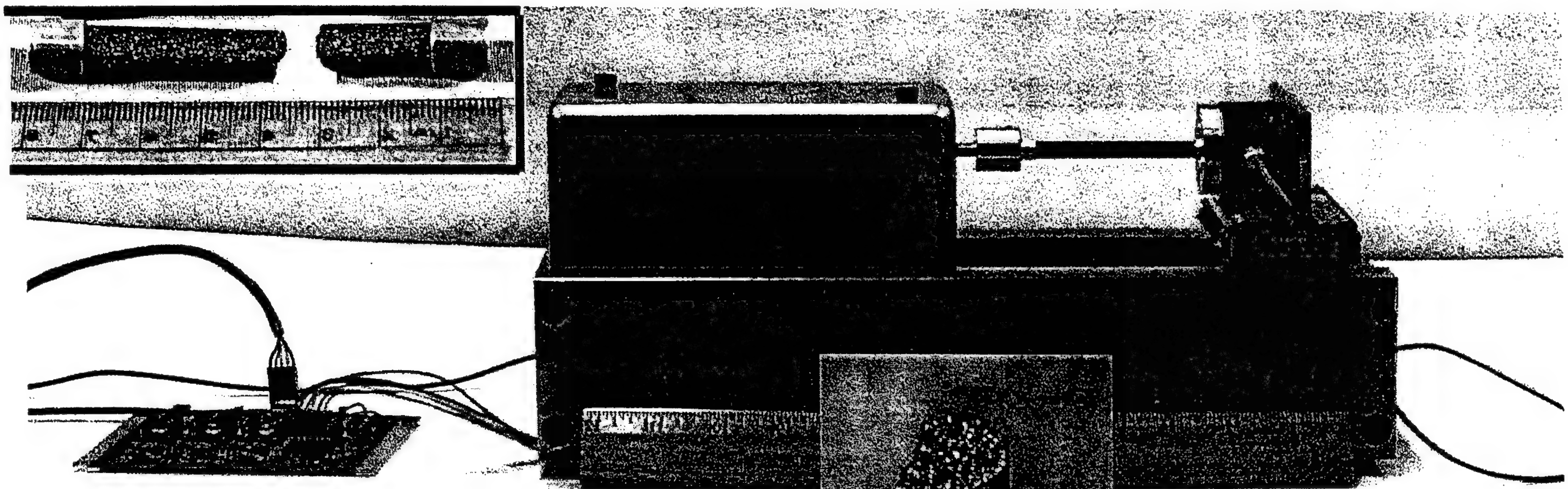
Nodes with Wedge & Twist Disclinations

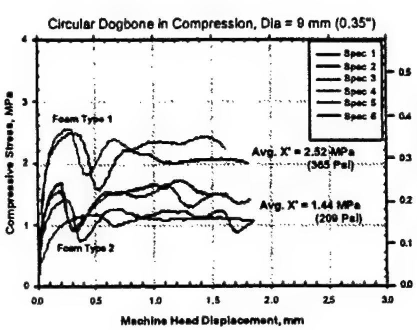


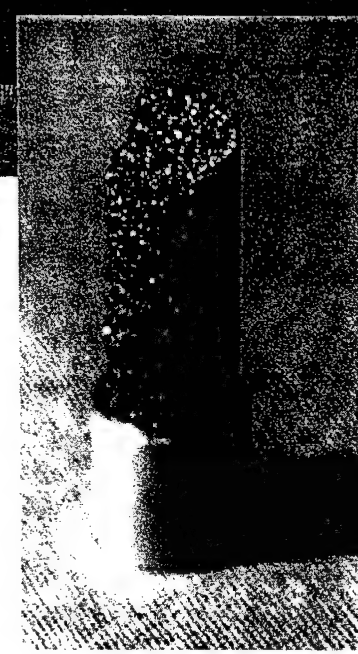


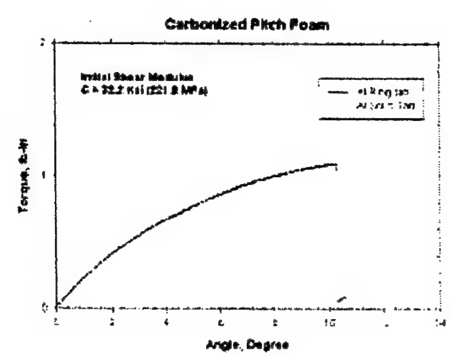


Test Method Development (Mechanical, Thermal)

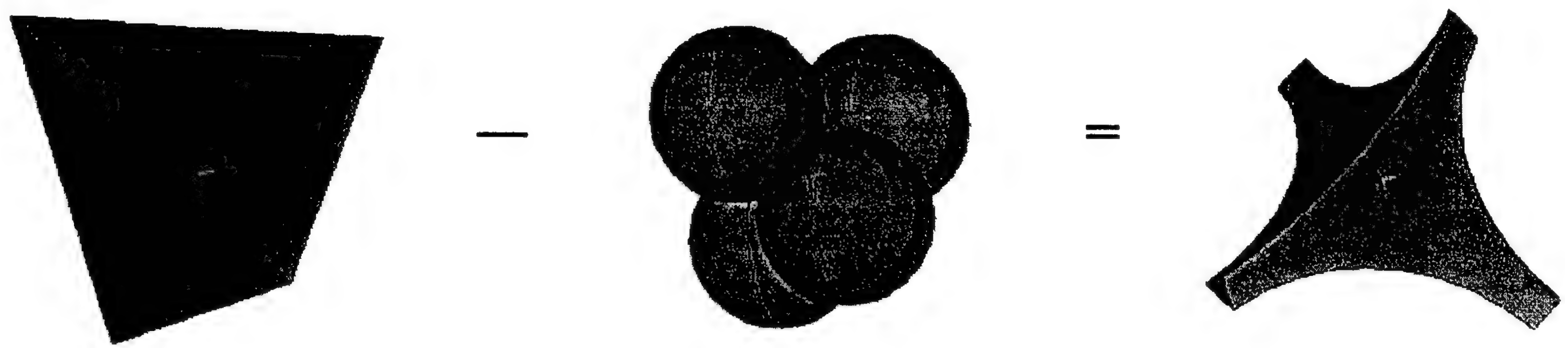




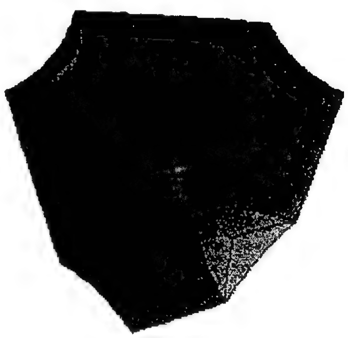




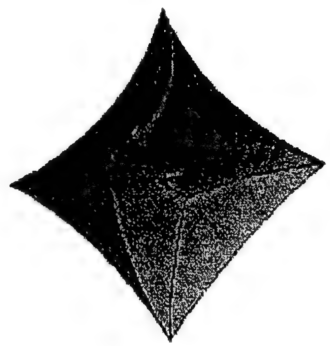
Modeling to Predict Properties



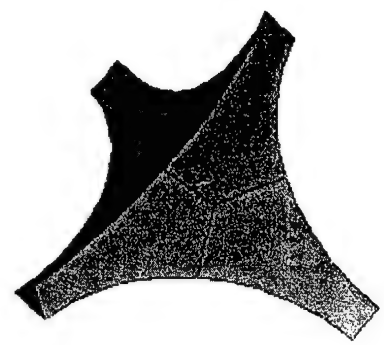
? ? 10%



? ? 78%

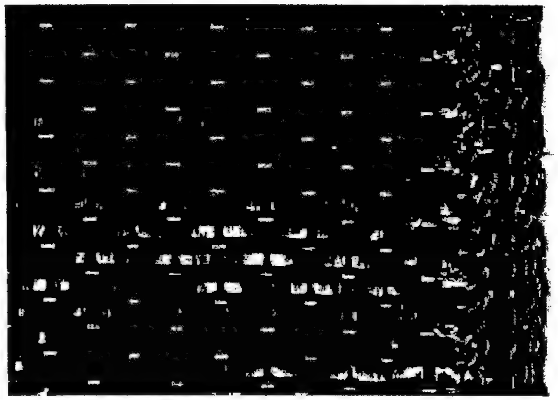


? ? 98%

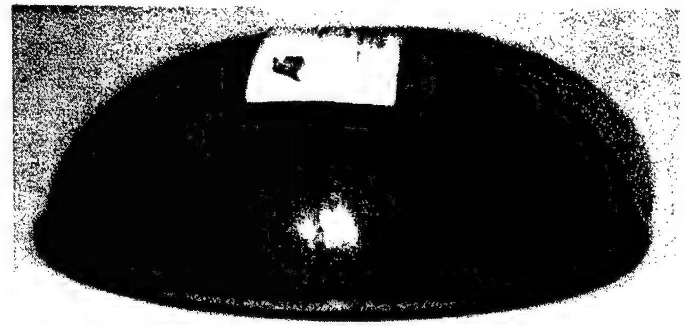


$$? ? 1 ? \frac{V_{cell}}{V_{tetra}} \quad : \quad \text{porosity}$$

Materials Development: Preformed Composites



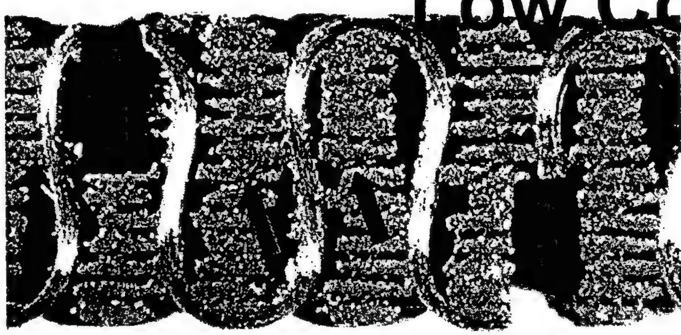
3D Weave (Z-reinforcement)



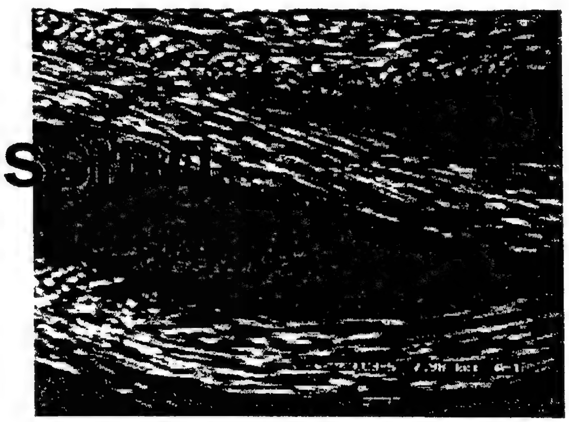
Processing Complex Shape

Enables

Low Cost Proces

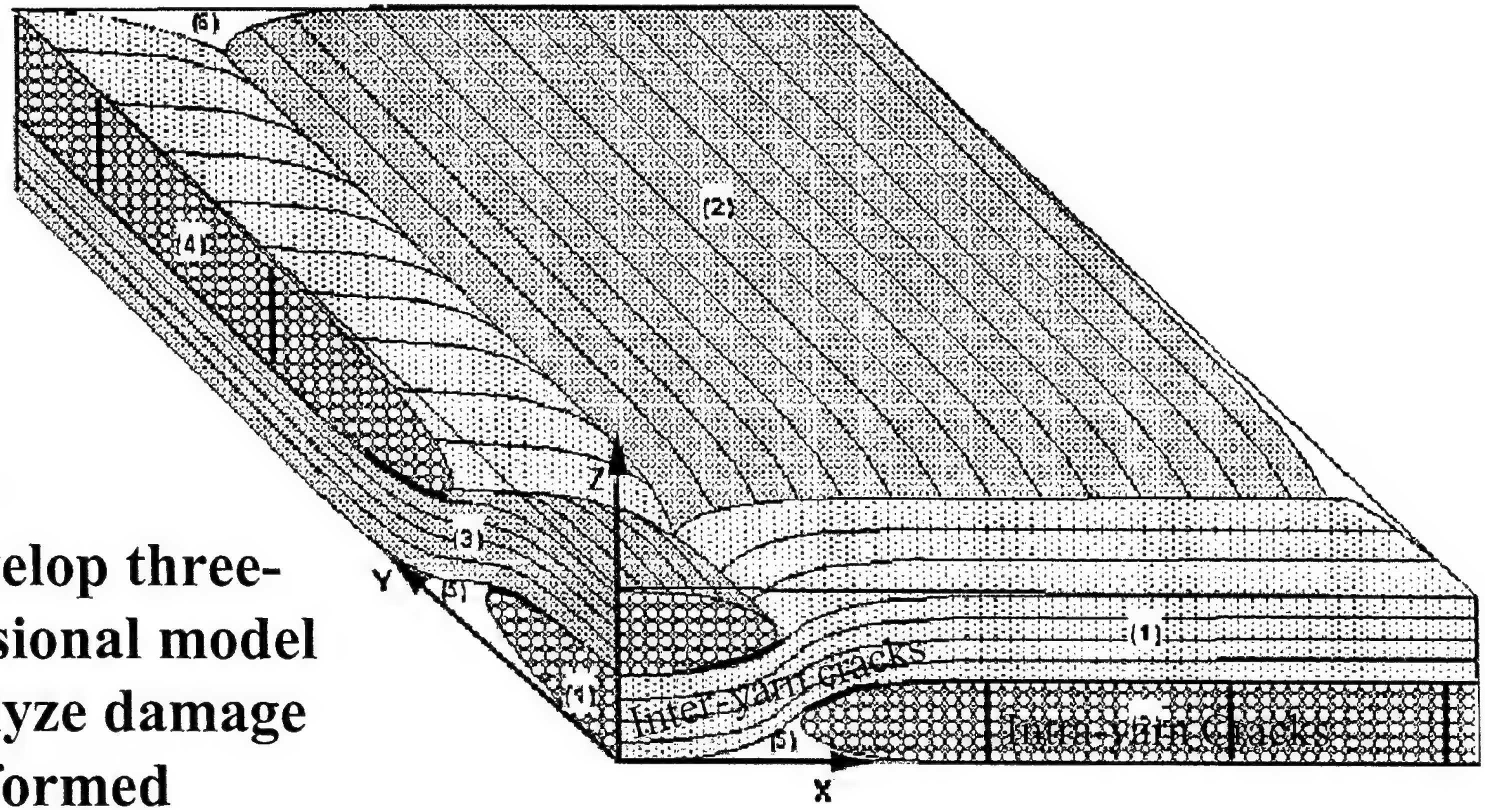


CMC (Z-reinforcement)



Angle Interlock - LO
Dimensional Control

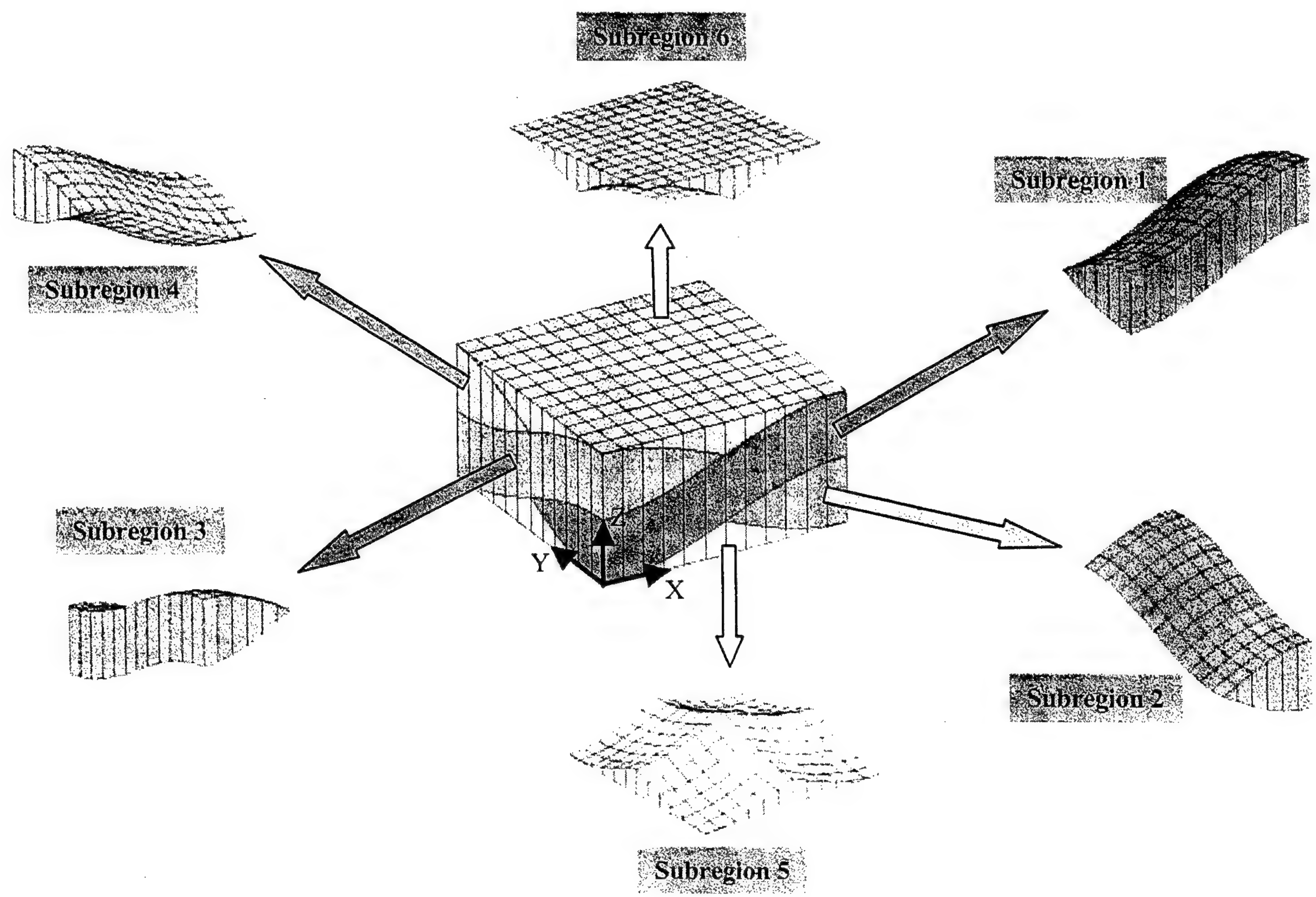
Fracture Mechanics of Preformed Composites



Objective:

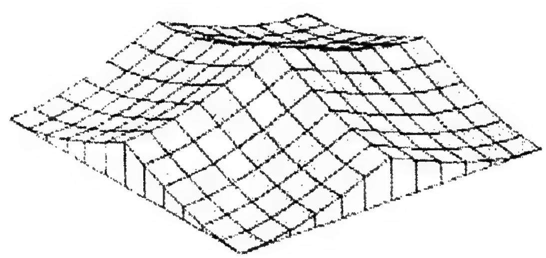
To develop three-dimensional model to analyze damage in preformed composite with fracture mechanics approach

Unit Cell of Plain-Woven Composites

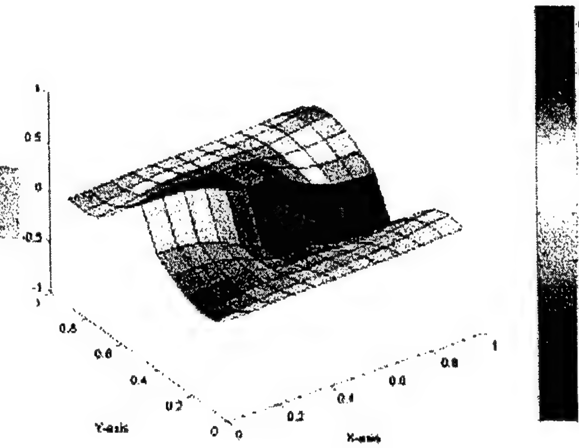


Interfacial Stress Distribution

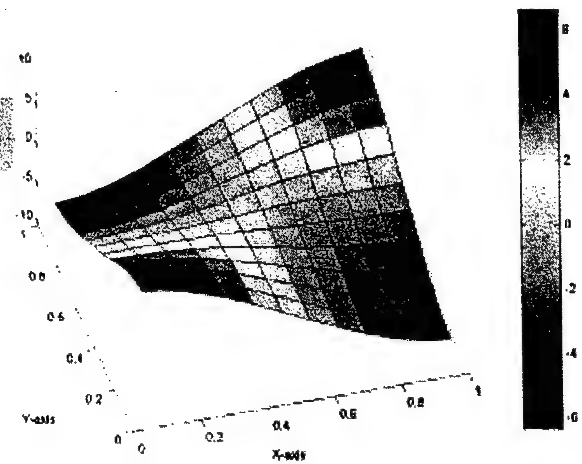
Subregion 5



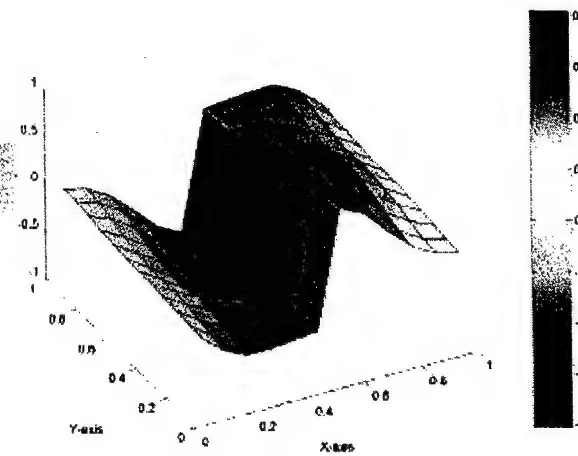
?yz

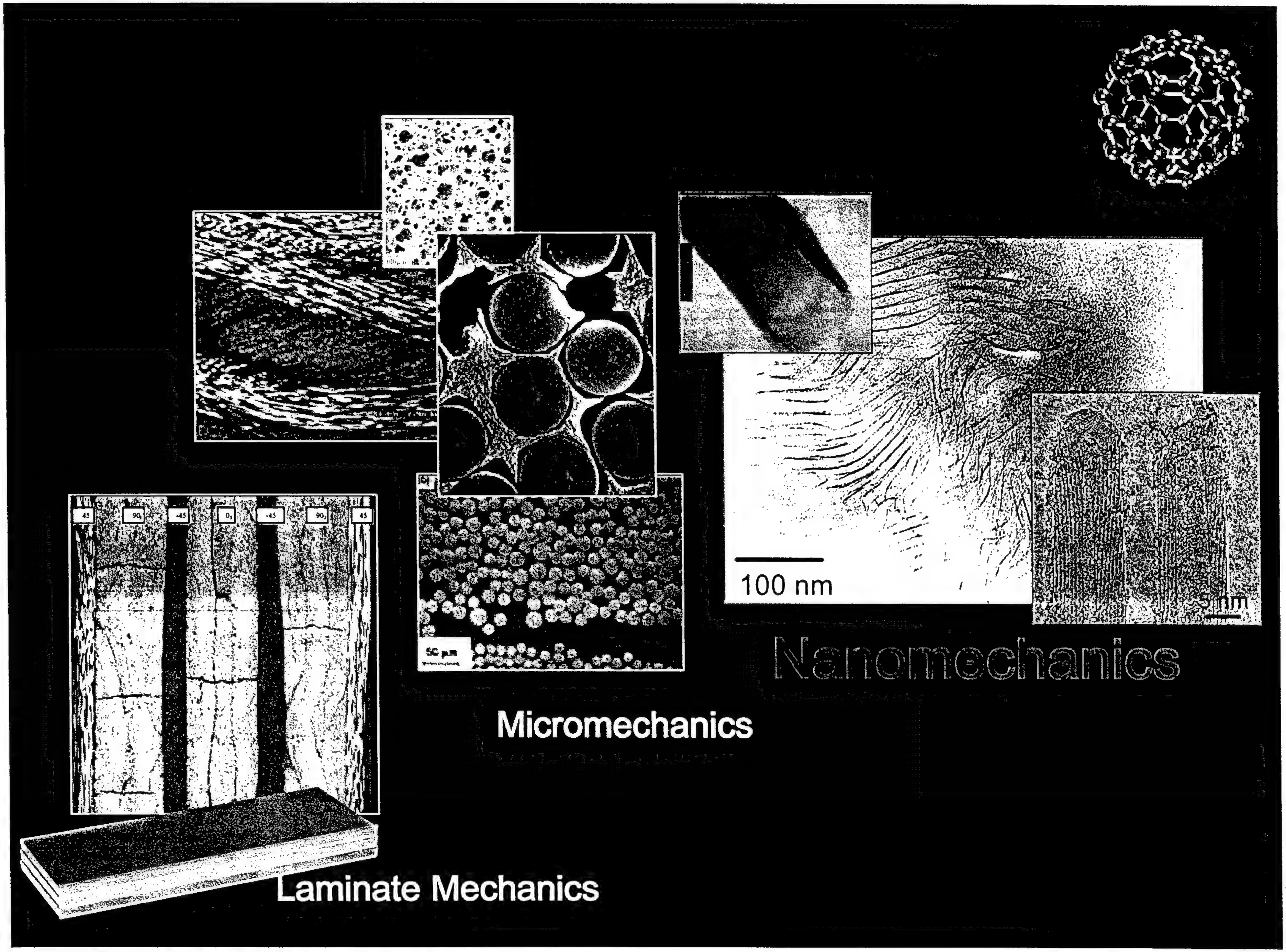


?z



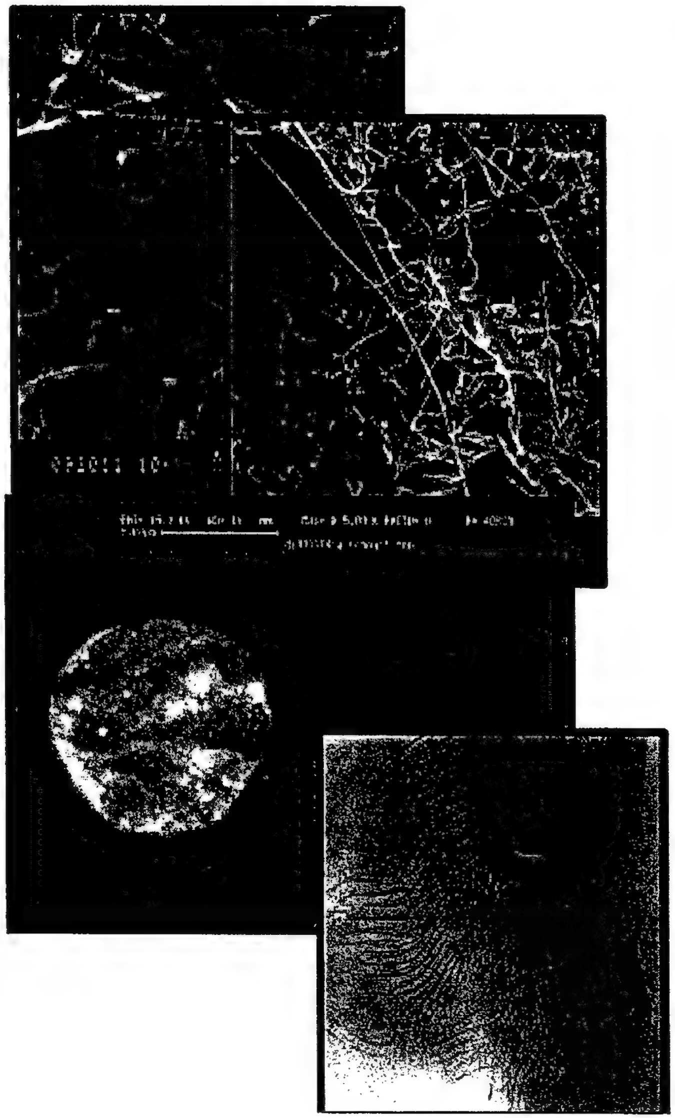
?xz





45
90
-45
0
-45
90
45
50 μm
100 nm
5 nm
Nanomechanics
Micromechanics
Laminate Mechanics

Material Forms…Challenges of Nanoscale



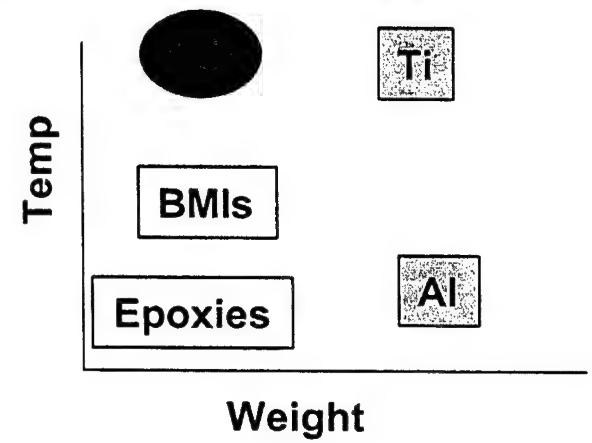
- <u>Model Material Necessary</u>
  - Well controlled morphology
  - Repeatability
- Resins (Suitable E, Tg, …)
- Nanoconstituent
  - Processability
  - Availability
  - Geometry/aspect ratio/1-2-3D
  - Potential for property enhancement
- Interface
- Fabrication: May need to look into 'new' techniques (IC fab'n, ..) or out-of-the-box constituents

Nano Composites Potential/Challenges

- Nanoconstituents offer an exciting new dimension of tailorability to composites
  - **Additional constituent for providing new behaviors to existing composites**
  - **Not just mechanical properties of interest – expect high interest in multifunctionality: CTE, electrical, thermal…**
- Fundamental understanding of the predictive processing-structure-property relationship must be addressed
  - **Necessary to enable manipulation and exploitation of nanomaterials**
  - **Key opportunity for mechanics community leadership**
  - **Focus required for advancement**
- Bring micromechanics/continuum, nanocomposites community and molecular modelers together to dialogue
- *Advocate unified focus; harness mechanics community*

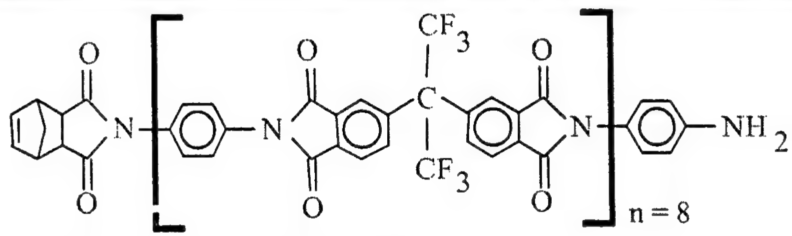
Extreme Environment: High Temperature Composites

Rationale

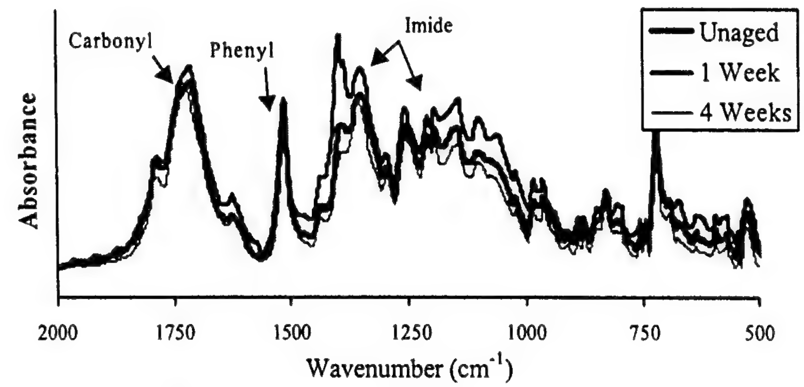


- Today: Military aerospace platforms require performance that is currently not met by nonmetallic systems
  - Ti primary material of choice
  - BMI qualified for use at 325°F
  - PMR-15, AFR-700B flying with issues
- Need: Reduced weight, reduced cost, special performance, fatigue…high payoff for many military applications
  - Airframes – high temperature primary and secondary structure
  - Engines
  - Exhaust washed structures
  - Launch vehicles
- Needs identified by multiple existing and future military platforms

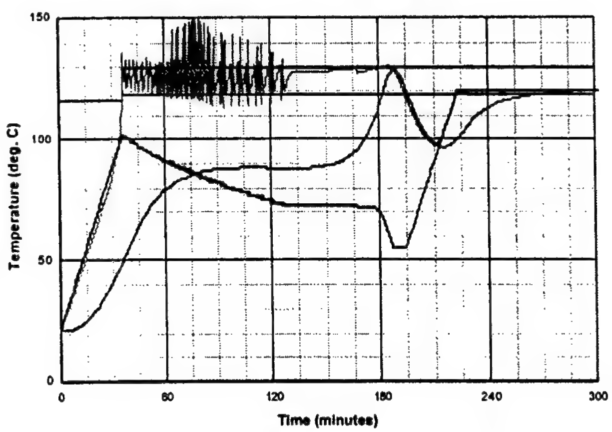
High-Temp PMC Research



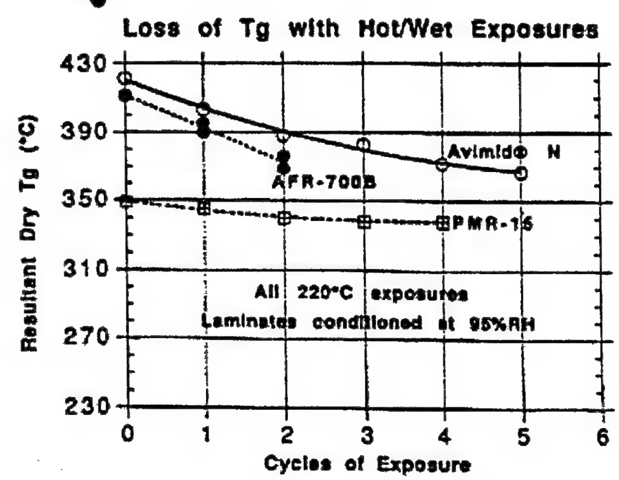
System Support
- SPOs
- Primes
- Other AFRL
- Contract Programs



Material



Process Development

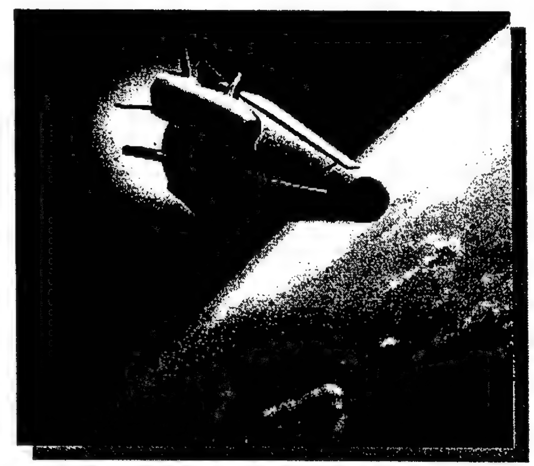


Service Life Performance

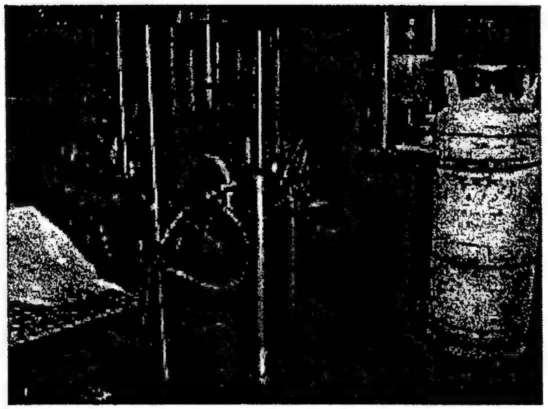
Extreme Environments: Cryo

Background

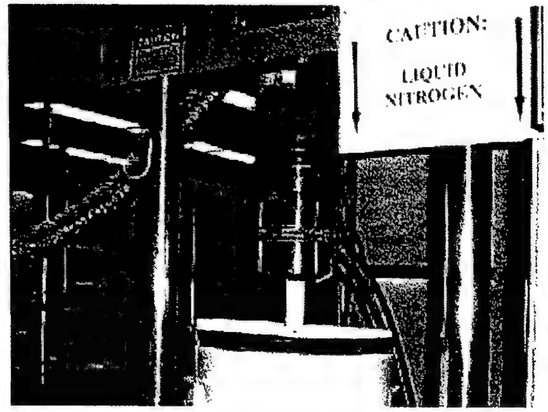
- Extensive use of PMCs is enabling for next generation civilian and military reusable launch vehicle concepts
- Use of PMCs proposed for structural cryotanks; limited number have been built
- Key is life and performance prediction including:
  - Microcracking and permeation
  - 1000s of thermal/mechanical cycles
  - Large temperature extremes: cryo (-253 °C for LH_2) to re-entry temp.
- Extremely limited test protocol / knowledge base available



Extreme Environments: Cryo
MLBC Cryogenic Capabilities



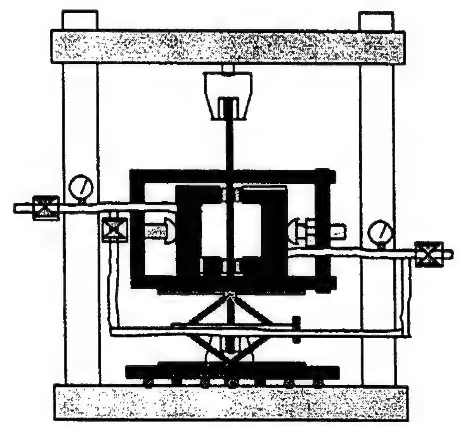
LHe Cryostat
+ mech load



LN_2 Cryostat
+ mech load, fatigue

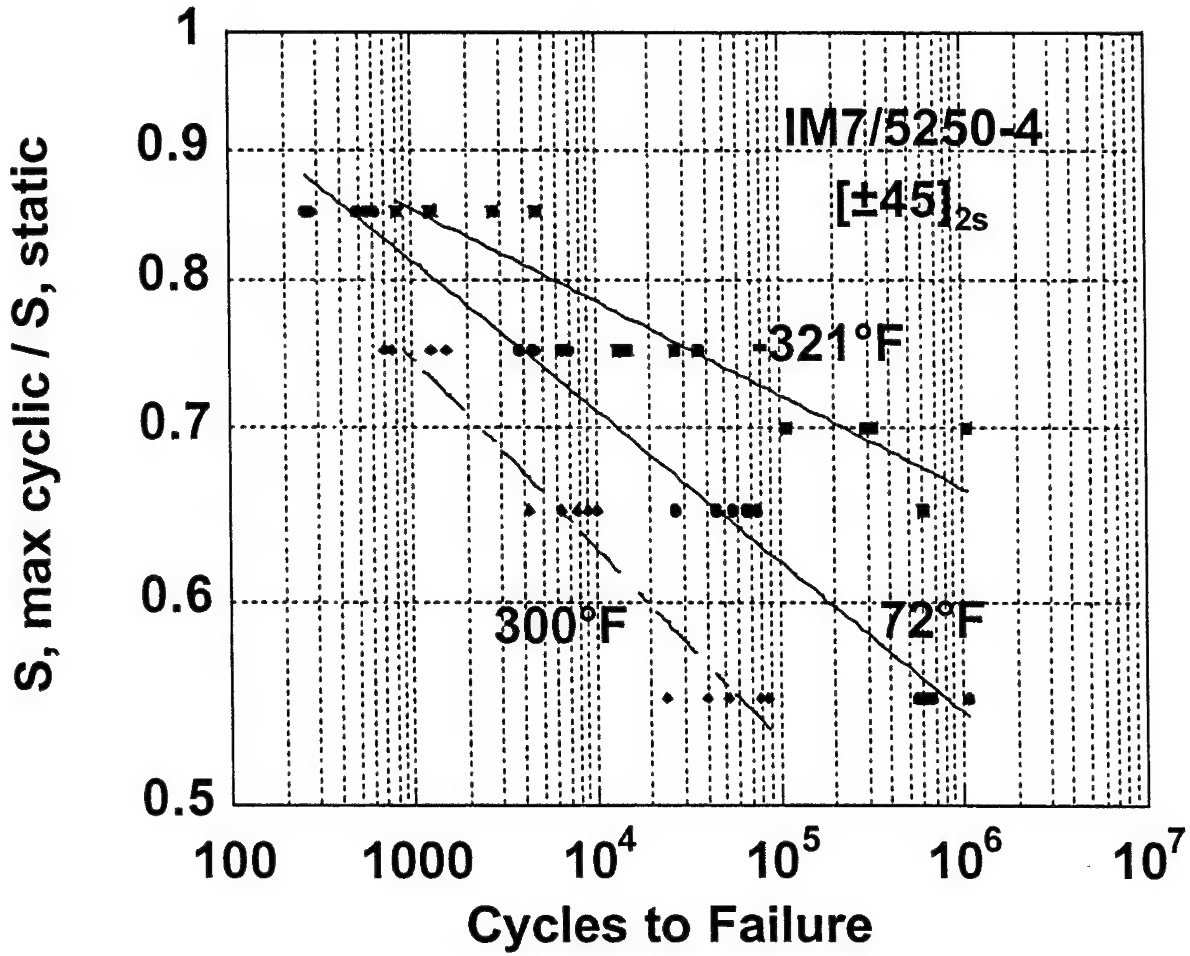
LN_2 / GHe Permeability

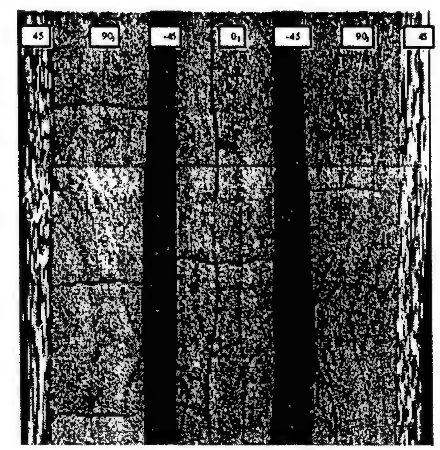
LN_2 Cryo/Thermal Cycler
+ constant mech load



LN_2 Permeability
+ mech load

Extreme Environments: Cryo Fatigue Data





Improved Capabilities: Thermal Management (TM) Materials

Rationale

- Challenge: Systems are becoming increasingly sophisticated. Structures are required to do more than perform load bearing or volume encasing functions-*multifunctionality*
- Thermal loads that must be managed are increasing as capability grows
- Pervasive in aerospace
- Military applications:
  - Aircraft:
    - Environmental Control System for C-130, F-22, JSF, F-18 E/F
    - Electronics cooling: F-22, JSF
    - Thermal Management: UCAV, Sonic Engine Cooling, Airborne Laser, Brakes
  - Spacecraft:
    - Minisats, Space Based Laser, Launch Vehicles

Improved Capabilities: TM Materials Strategy

ASC
AFRL/VS
AFRL/VA
Industry

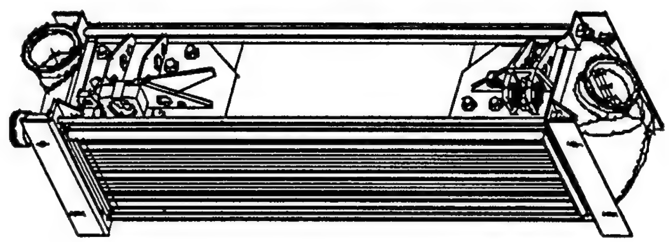
Users Needs → Innovative Carbon OMCs → Focused Demonstrations (Quantified Payoffs) → Future.... More Functionality

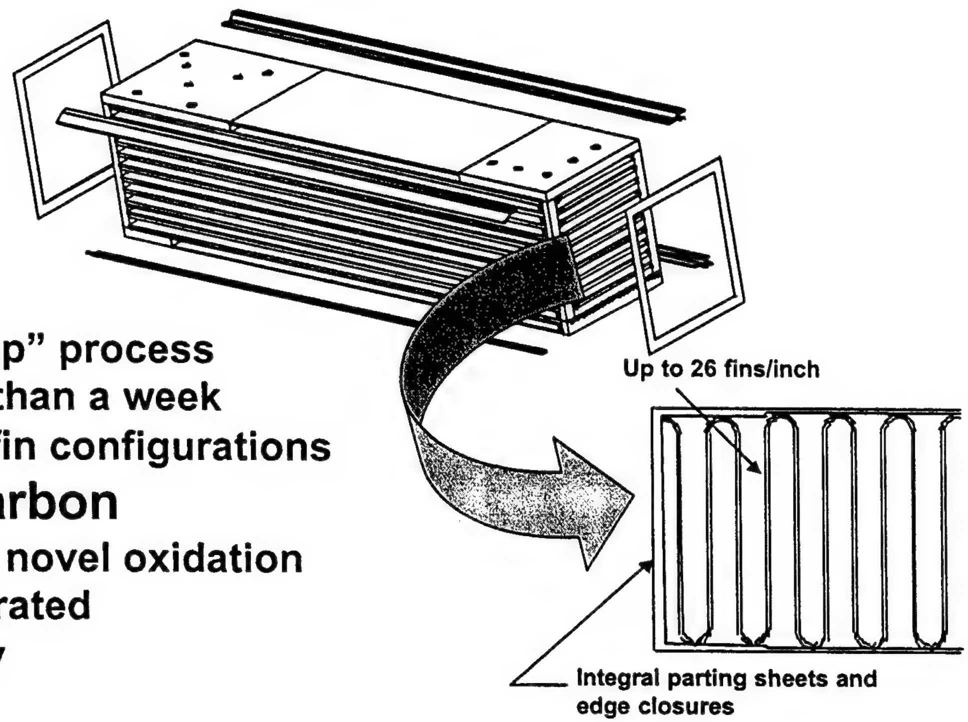
Carbon Carbon
High Conductivity Forms
Carbon Foams
Carbon Nanotubes

Heat Exchangers
Aircraft Brakes
Thermal Doublers
Thermal Planes
Single Use Thermal Protection System
Reusable Thermal Protection System
Advanced Aircraft Brake Technology

TM - Air Applications
Materials Technology Development

Thermal Management for Heat Exchangers





Low Cost Carbon-Carbon
- Multiple approaches to a “one-step” process
- Reduces processing time to less than a week
- Enables thin walled high density fin configurations

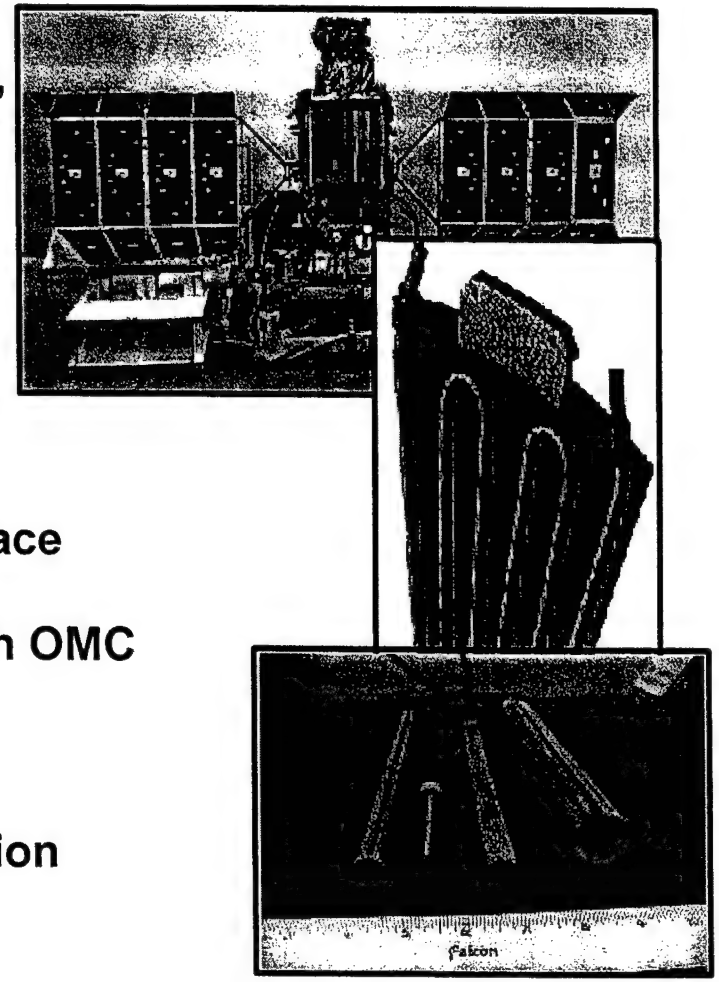
Oxidation Resistant Carbon-Carbon
- 1200°F temperature goal requires novel oxidation schemes not previously demonstrated
- The use of inhibitors is necessary

Extends time between failure by 2X

Extend range due to 40% weight reduction and increase heat exchanger efficiency by 10%

TM - Current Programs: Non-metallic Heat Pipes

OMC Heat Pipes



Why OMCs?

- The trend towards OMC structures for weight, stiffness and dimensional stability has driven the need to have composite radiators
- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues

Technical challenges of OMC heat pipes:

- Non permeable – $2x10^{-10}$ scc/sec He
- CTE match of hybrid OMC material and interface joint material – ? CTE – 0 to 1 ppm/K
- Integration of thermal efficient heat pipes with OMC skins and honeycomb core components
  - Fewer heat pipes per radiator possible
    - Less weight
    - Less complex design and fabrication processes

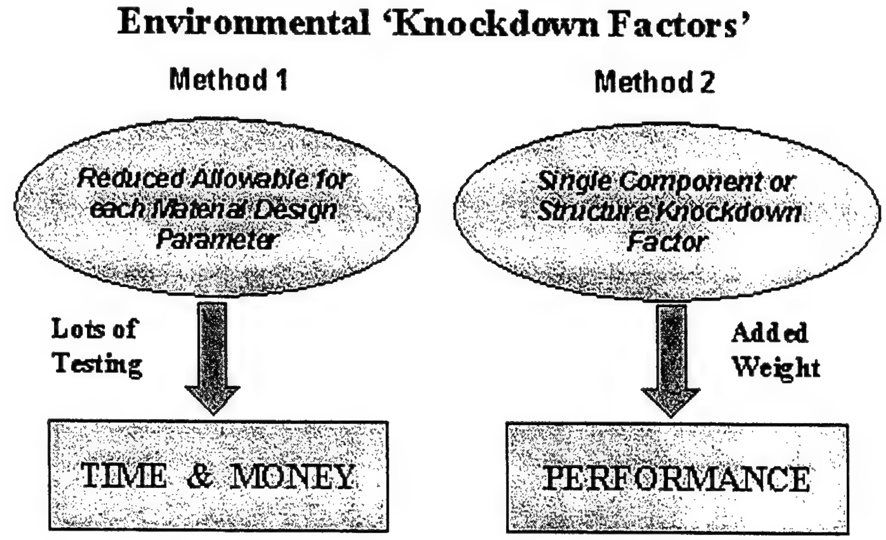
The use of OMC reduces component weight (i.e. up to 10-20%)

PACT: Parnership for Advanced Composites Transition

New and innovative composite systems can enable advancements in aircraft design and operational limits

HOWEVER

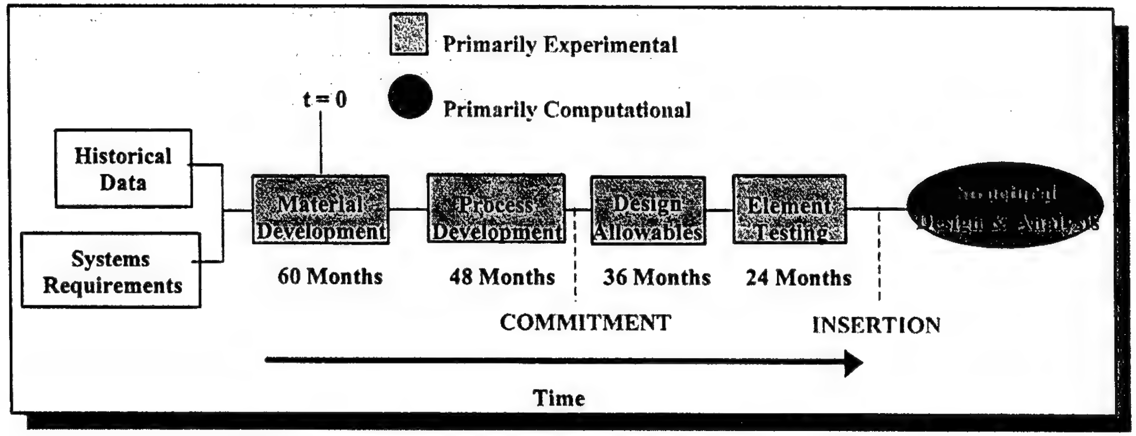
- Knockdown factors for environmental effects, effects of defects, etc. based on worst-case assumptions lead to unrealistic, excessively conservative designs.

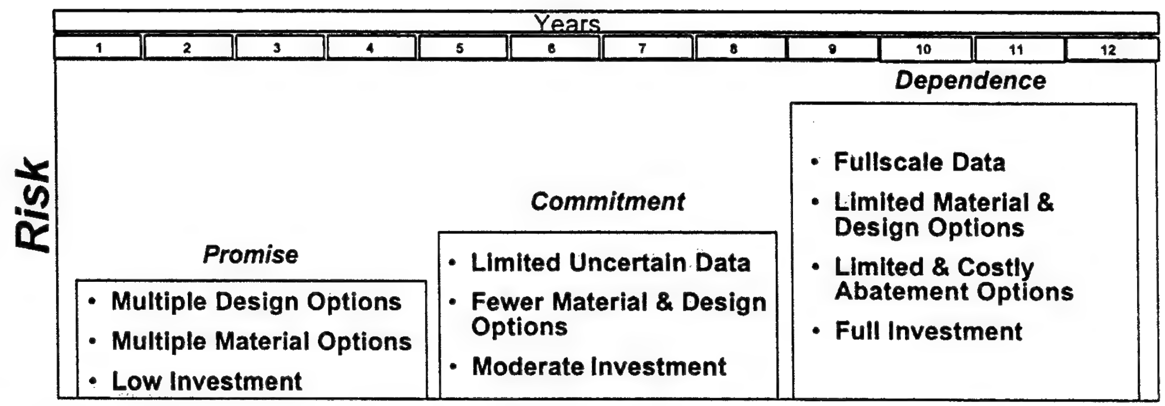


- Knockdown factors (resulting in weight penalties) often remove composites from systems during EMD phase.

Motivation for PACT

- Complex 12+ year cycle
- Most data generated after commitment
- Producibility and performance issues are identified at a time when:
  - –design options are limited
  - –abatement is costly
- Uncertainty creates risk for designers throughout the cycle

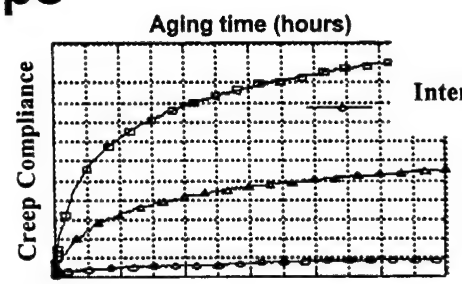


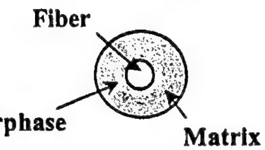


Designers Need to Get Earlier Data with Less Uncertainty to Lower Insertion Risk

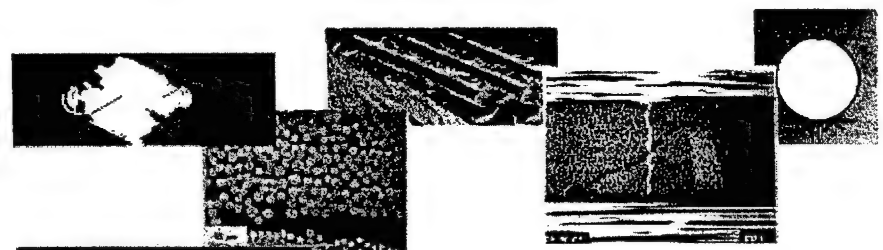
PACT: Grand Challenges

- Processing/property relationships

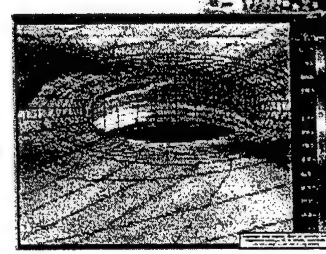




- Chemistry/mechanics linkage
- Lack of robust/validated failure criteria

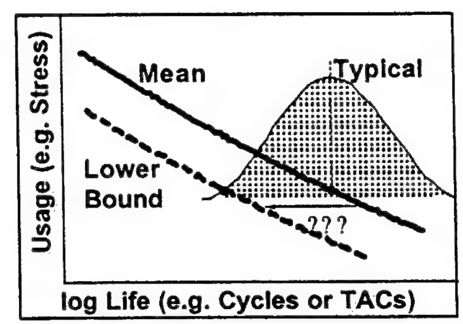


- Development of accurate deterministic engines

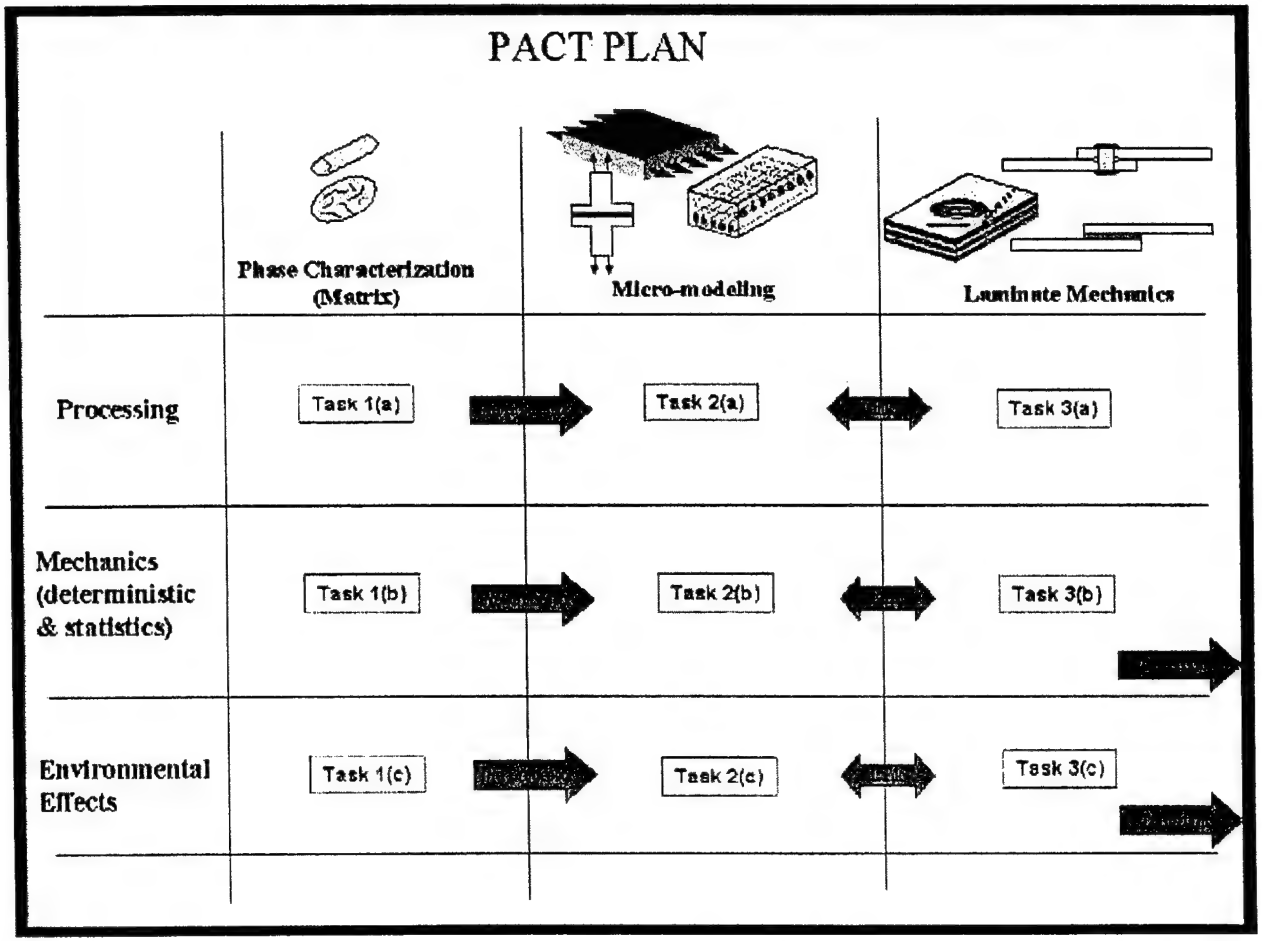


[-45/90/45/-45/45/0$_3$/? 45*]

- Statistical variability in materials, process, handling and loading



PACT: Hierarchy of Models



- *Interdisciplinary task linkages are prime motivation*
- *Interdisciplinary programs are required*
- *Polymer Science and Mechanics expertise in MLBC*

Complements AFOSR – MEANS Program

B-Spline Analysis Method (BSAM)

- 3-D Geometries
- p-, h-, and b-spline approximations
- 21- constant thermo-elasticity
- fracture mechanics

$$u(x,y,z) ? \underset{i}{?} \underset{j}{?} \underset{k}{?} U_{ijk} ?X_i(x) ?? Y_j(y) ? Z_k(z) ?$$

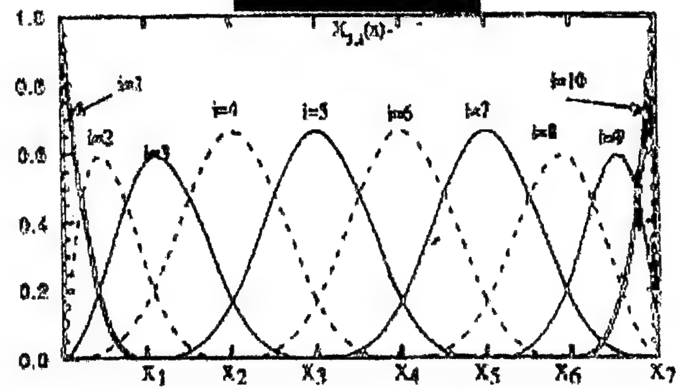
u ? continuous at all points

$\frac{?u}{?x}$? continuous at all points

$\frac{?u}{?y}$? continuous at all points

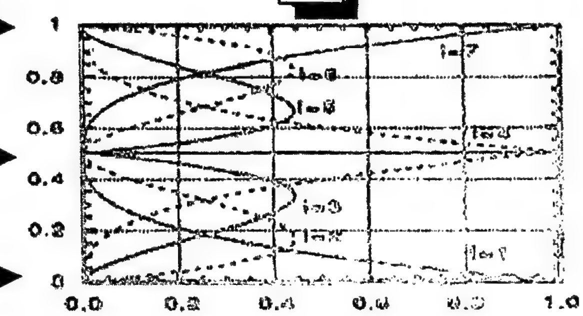
$\frac{?u}{?z}$? discontinuous at ply interfaces

X_i and Y_j



Z_k

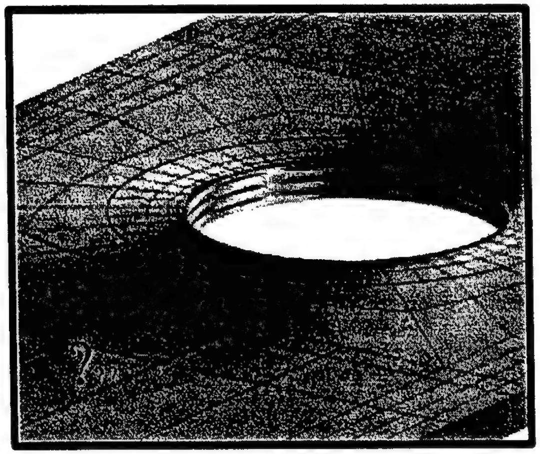
Ply Interfaces

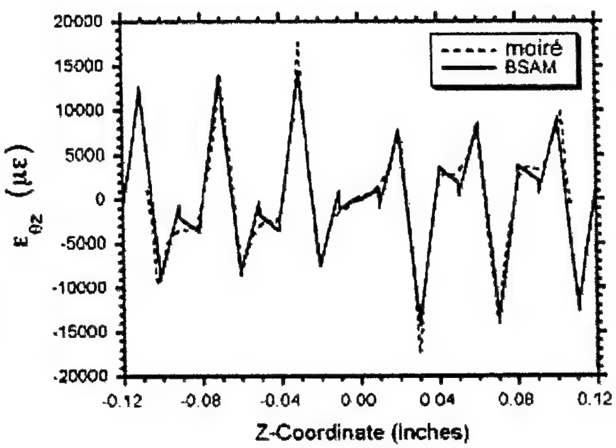


Similar to the old SVELT, but <u>much</u> more flexible!

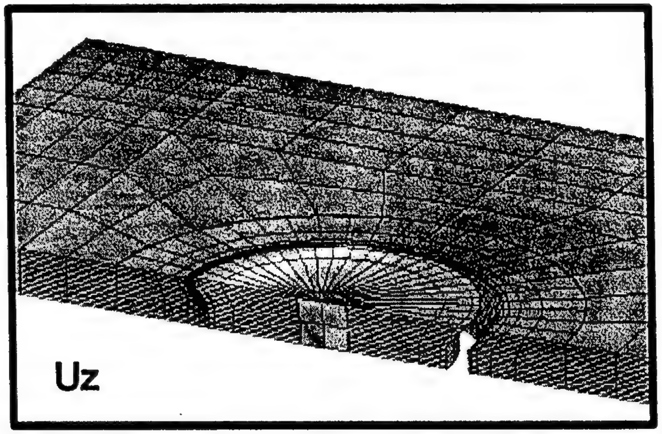
Capabilities

Validated Open-Hole Solutions

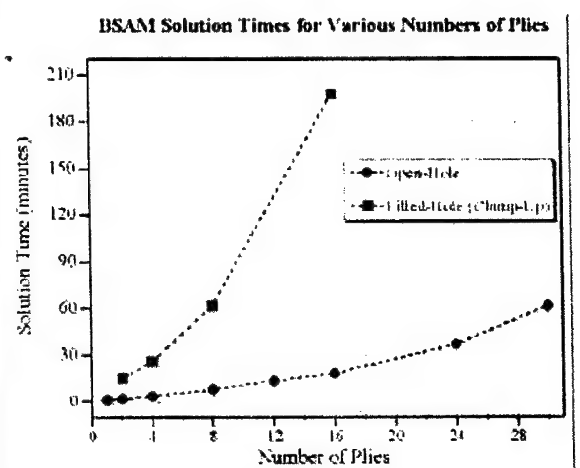




Filled-Hole Analyses

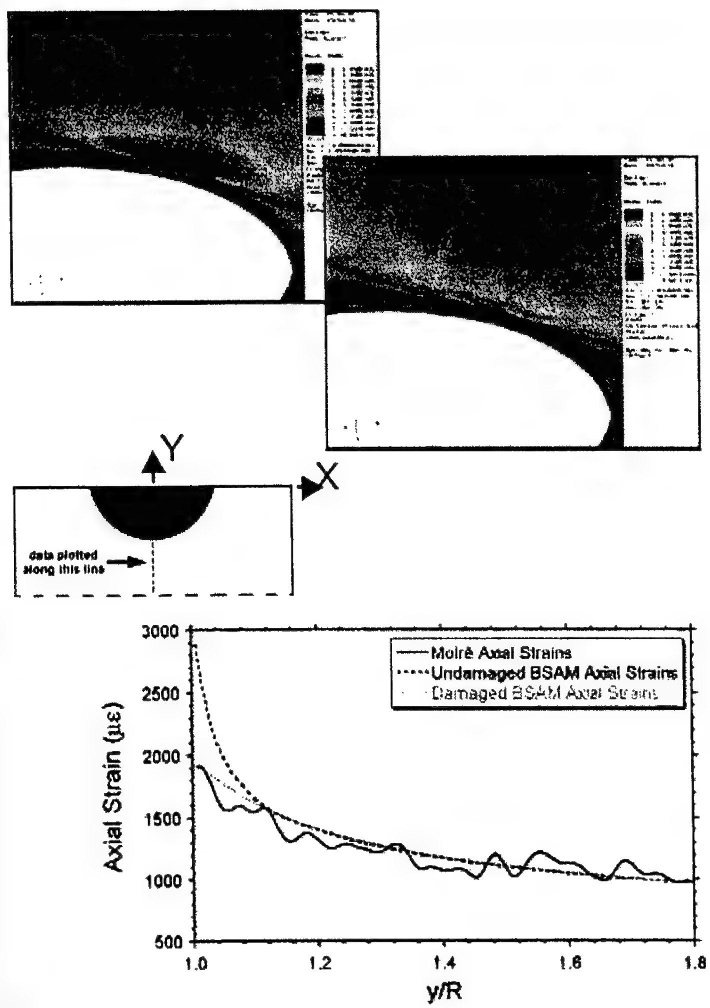


Quick Solution Times

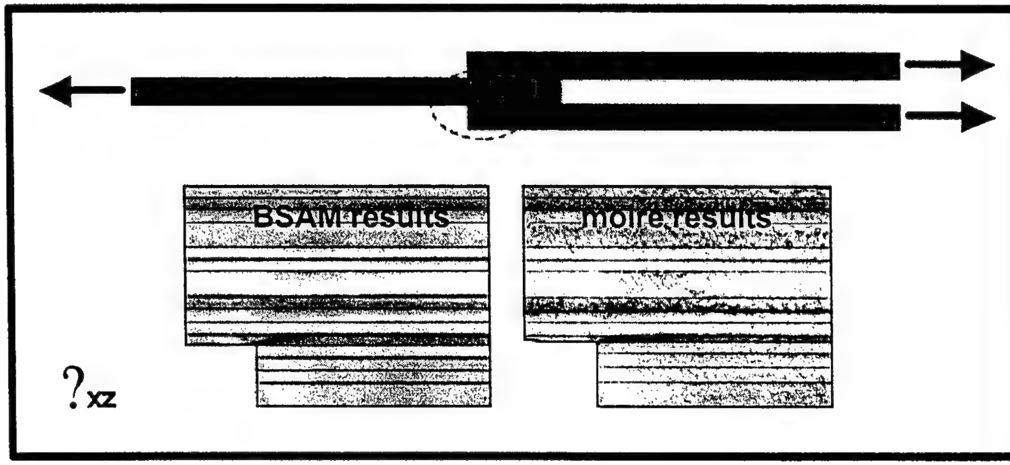


Capabilities

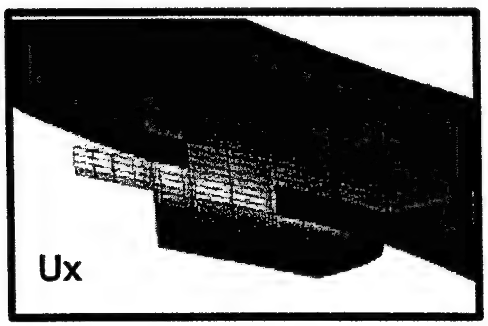
Mesh-Independent Crack Modeling



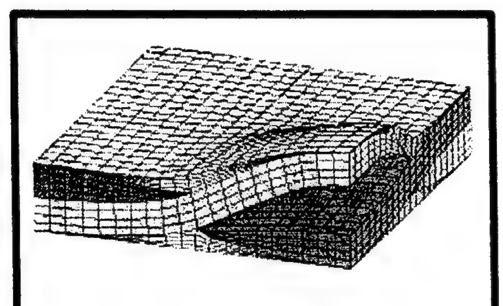
Bonded Lap-Shear Joints
(with residual stresses)



Bolted Joints



Woven Architectures



Summary

- Critical mass group: 26 government / 9 on-site professionals / 8 technicians
- History of innovation and transition of composites technology
- Enthusiasm, expertise, and ideas to keep the composites revolution alive

Overview of Research Activities at AFRL Space Vehicles Directorate

23 Oct 02

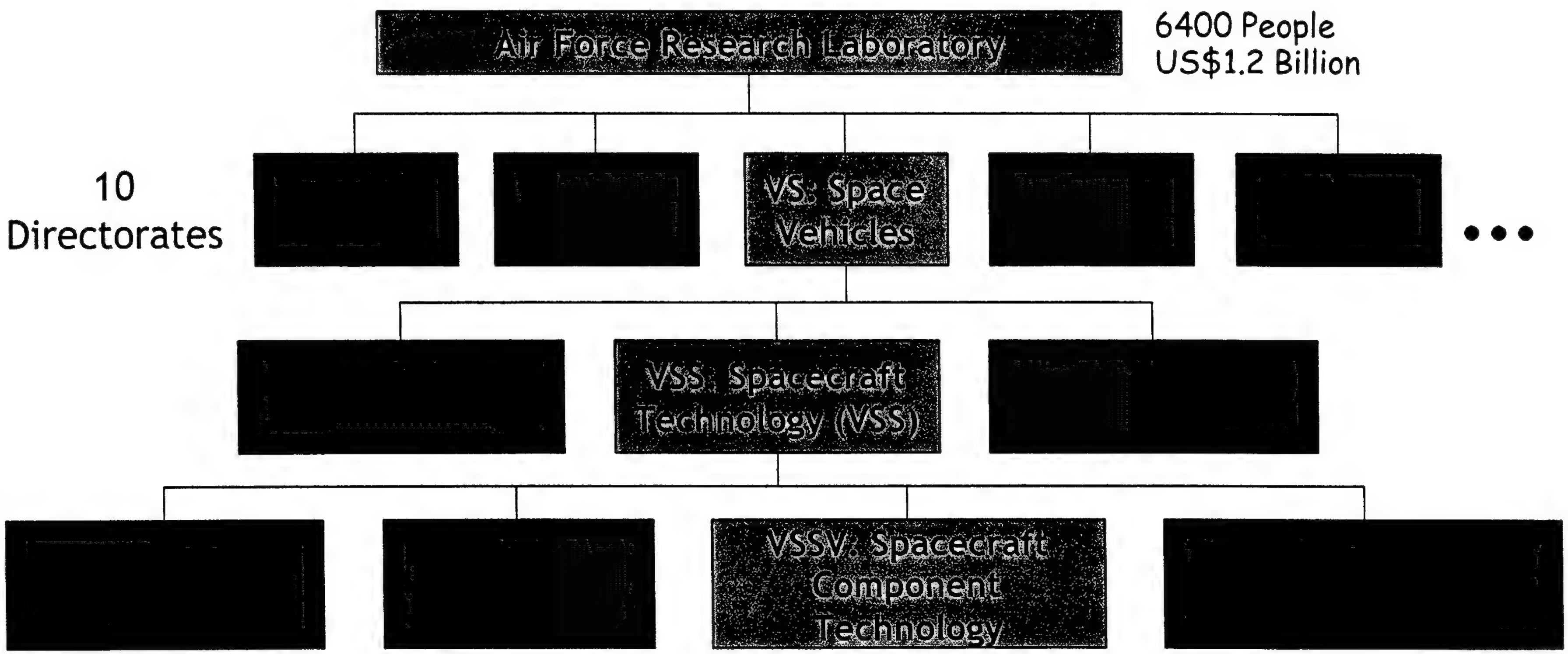
Jeffry S. Welsh, Ph.D.

Aerospace Engineer

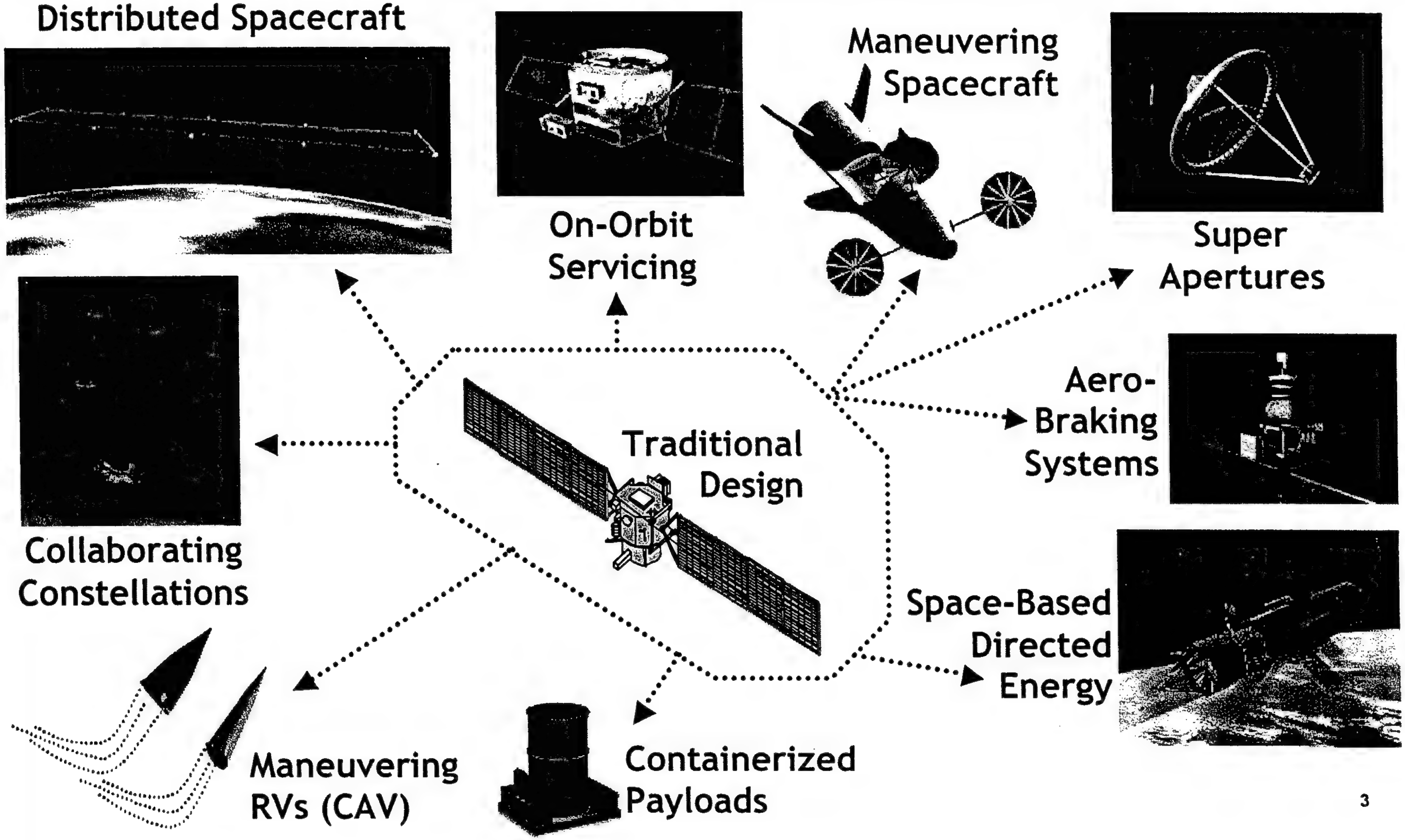
Space Vehicles Directorate

Air Force Research Laboratory

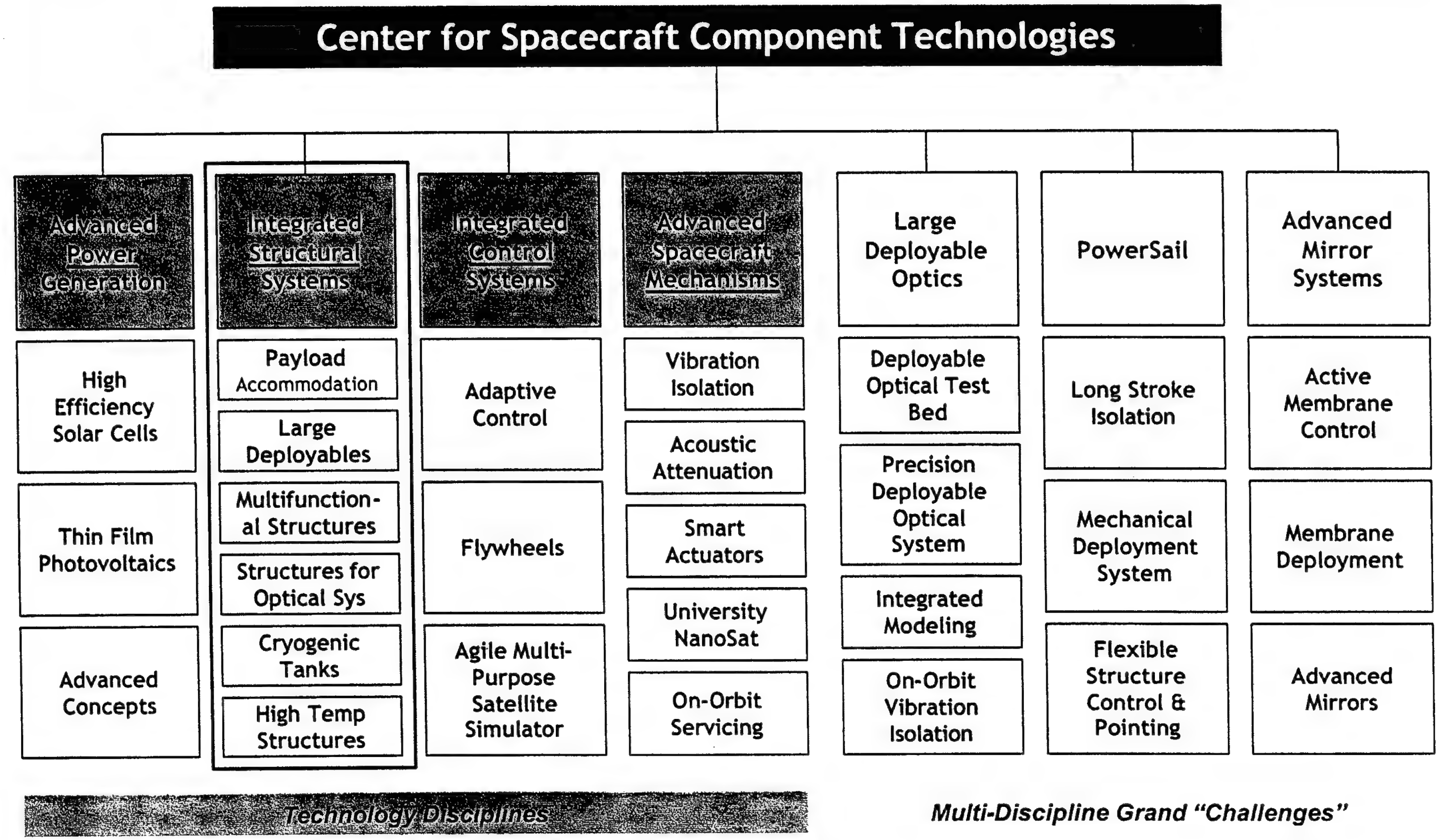
Spacecraft Component Technology (VSSV)
Our Position Within AFRL/VS



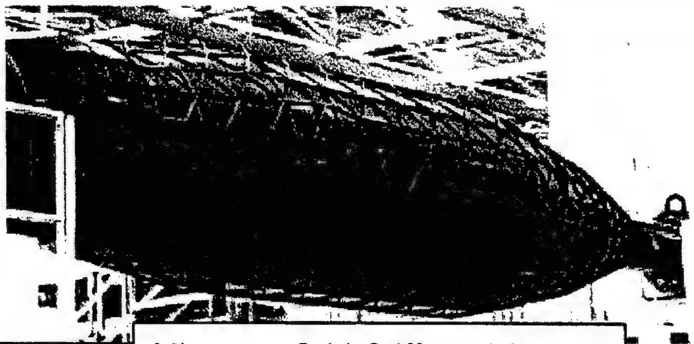
Goal: Enabling Technologies for Future Space Architectures



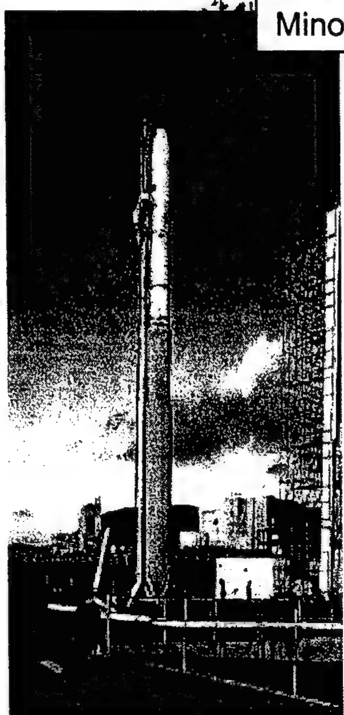
Spacecraft Component Technology
Research Thrusts



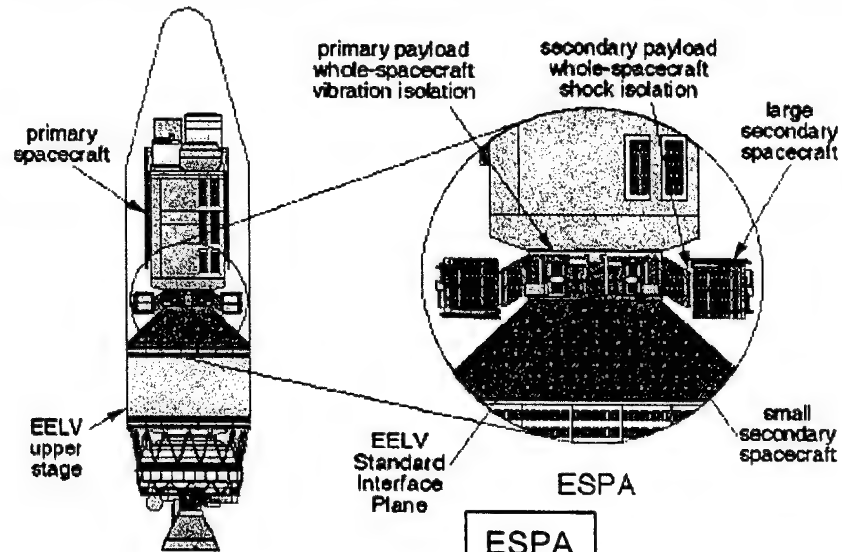
Integrated Structural Systems
Payload Accommodations



Minotaur Grid Stiffened Fairing



Minotaur Grid Stiffened Fairing



ESPA

- Decrease cost of space access with innovative design and manufacturing
  - Fairings
  - Adapters
  - Payload containers for Reusable Launch Vehicles
- Enable launch of large space systems with large payload fairing development program

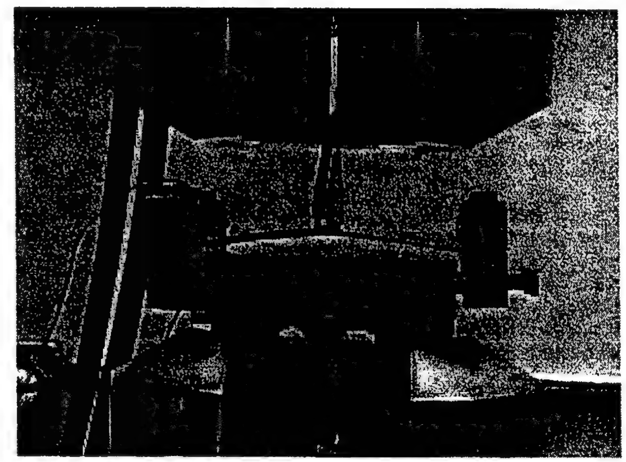
Low-Cost Fabrication of Advanced Grid-Stiffened Structures

Results

Table 1. Comparative Results

Design	Base-line	Option 1	Option 2	Option 3	Option 4	Option 5
Average failure load (lbs/inch of joint)	76.8	173.7	200.7	121.1*	167.0	233.4
Percent of Baseline	100	226	261	158	217	304
Testable Coupons	2	1	1	1	3	3

* specimen failed in rib above the staples, not at the joint



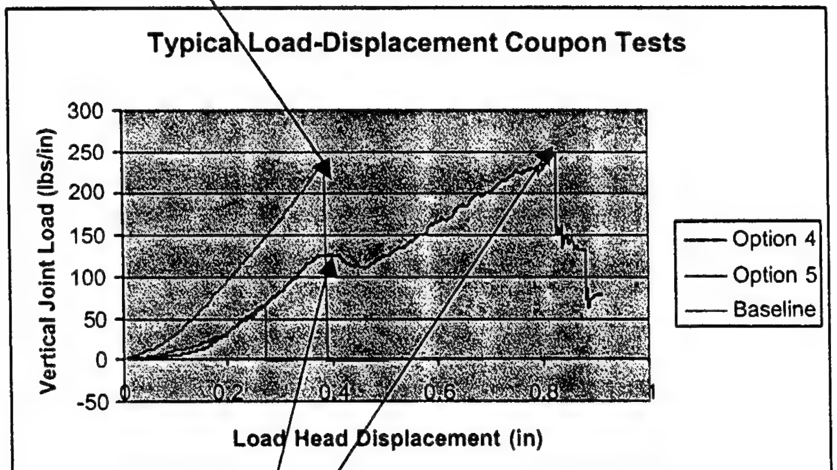
Typical coupon test approaching failure load

Low-Cost Fabrication of Advanced Grid-Stiffened Structures

Results

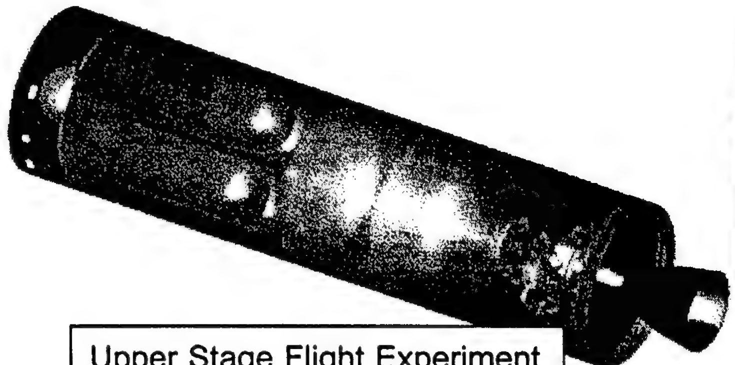
- All options improved joint performance
- Options reducing peeling stress worked better compared to direct reinforcement techniques
- Direct reinforcement ultimate strength was high but initial failure strength must be used for design

Low peel stress option (initial and ultimate failure coincident)



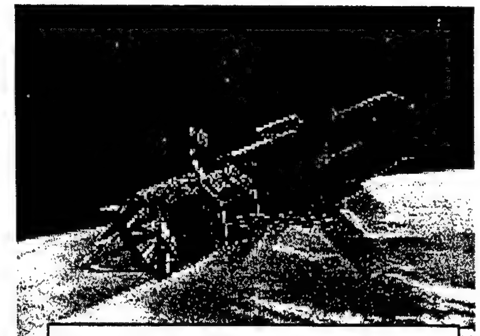
Direct reinforcement option (initial failure much lower than ultimate)

Integrated Structural Systems
Cryogenic Tanks

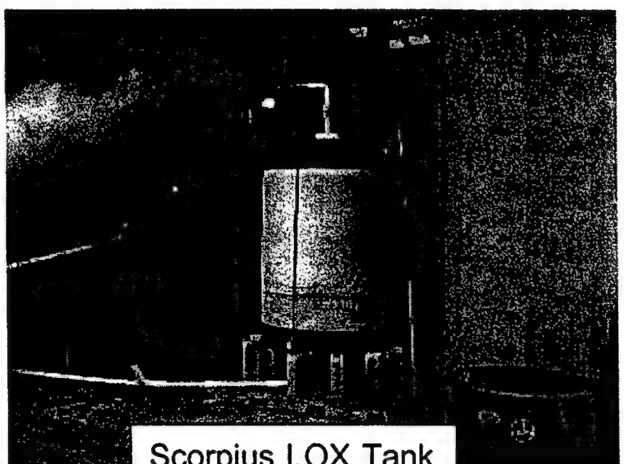


Upper Stage Flight Experiment

InterWeave Winding



Long Term Cryo Storage



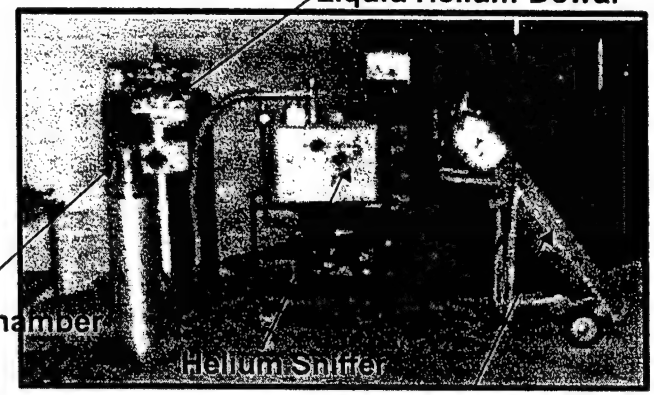
Scorpius LOX Tank

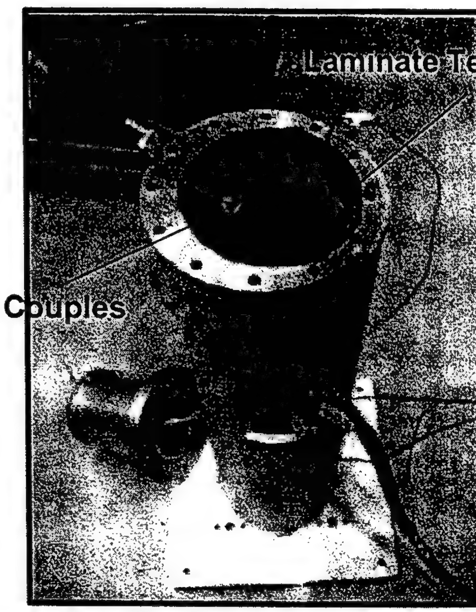
- Enable Single Stage to Orbit (SSTO) with composite cryogenic storage tanks
- Provide lighter, less costly tanks for long term on-orbit storage of cryogens
- Reduce cost of space access thru low cost cryo tanks for expendable rockets

Composite Laminate Microcrack Mitigation

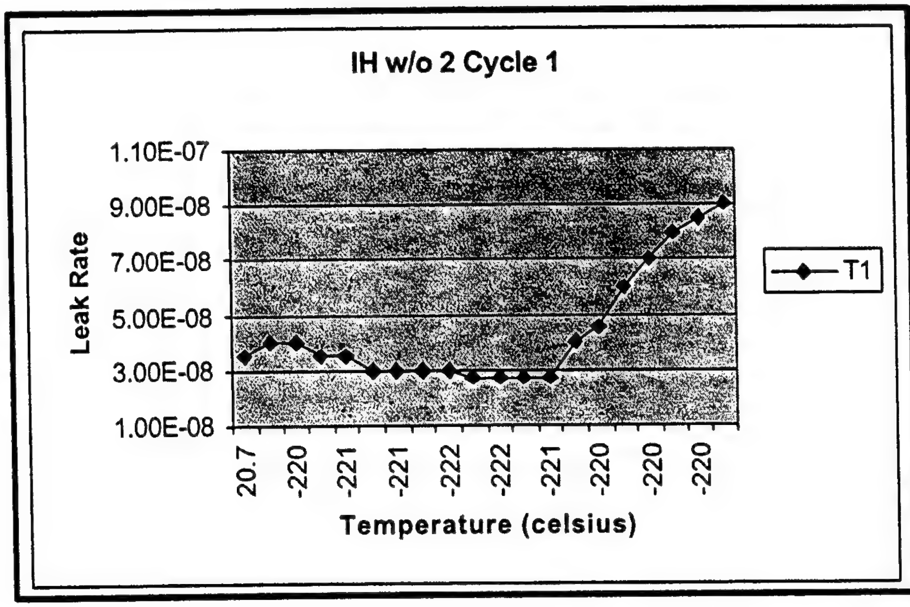
Introduction/Background

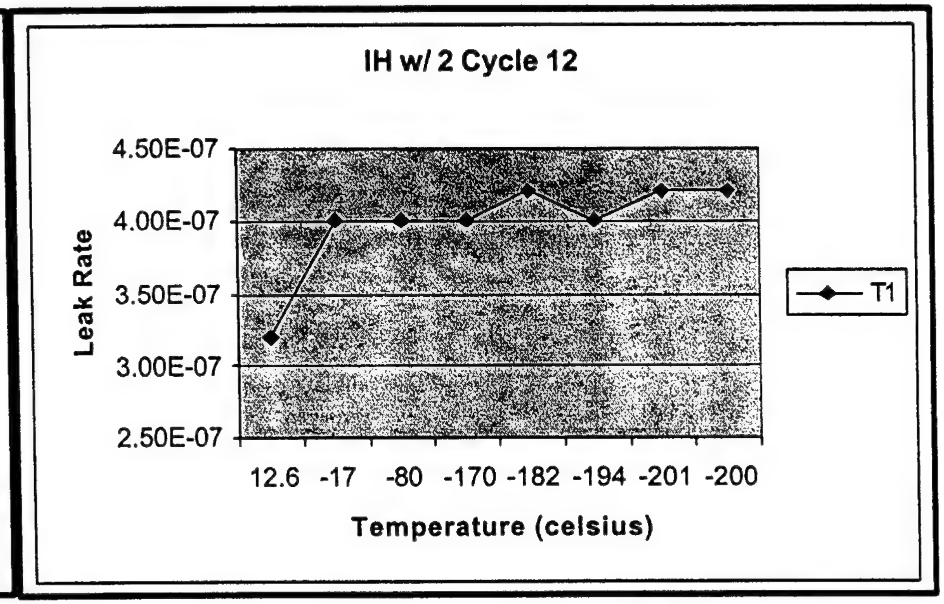
- Objective: Develop Manufacturing Processes, & Novel Material Concepts to Delay, Reverse, Prevent, or Stop Composite Laminate Microcracking under Extreme Thermo Cycling.
- Background: Space Community unsuccessful thus far developing cryogenic composite tankage, forced to use Metallic Tankage (Payload margin not optimized).
- Current Focus: Self Healing Laminate, & Laminate Surface Texture Research
- Operational Benefits
  - 50% Less Mass than Metallic Tanks
  - Enabling for SSTO, Reusable Vehicles
  - Reduced Tank Fabrication Costs





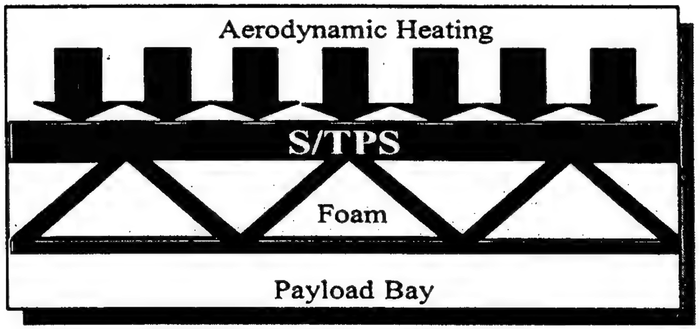
Composite Laminate Microcrack Mitigation
Results



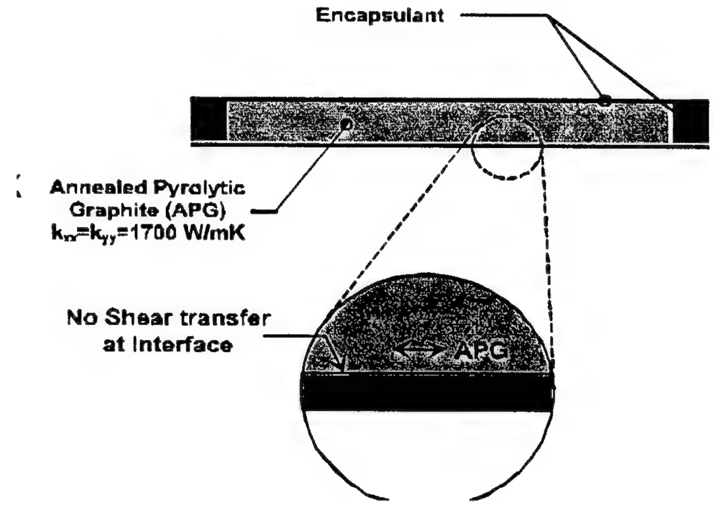


- Data Summary - Results as Expected
  - Leakage Increases as Temperature Decreases
  - Slight Leak Rate Decrease during “Heatup” to Ambient
  - Fiber/Resin CTE Difference Primary Cause of Microcrack
  - Need additional data on Omni-Directional Fabric

Integrated Structural Systems
High Temperature Structures



Integrated TPS and Load Bearing Structure

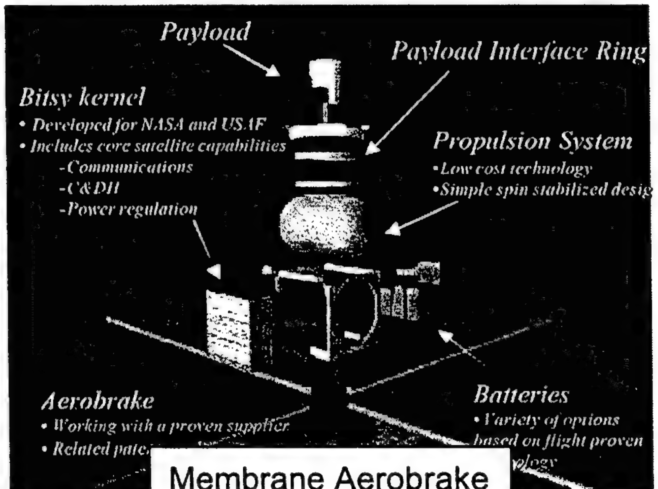


Annealed Pyrolitic Graphite

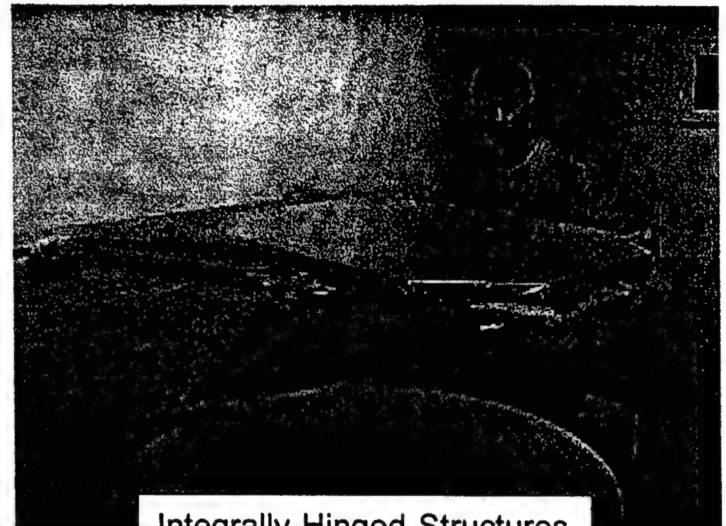
Low Cost Ablative Nozzle

- **Enable Single Stage to Orbit (SSTO) Reusable Launch Vehicles**
  - **Integrate TPS and Structure into hybrid system**
  - **Low maintenance between sorties**
  - **Low cost**
  - **Light weight**

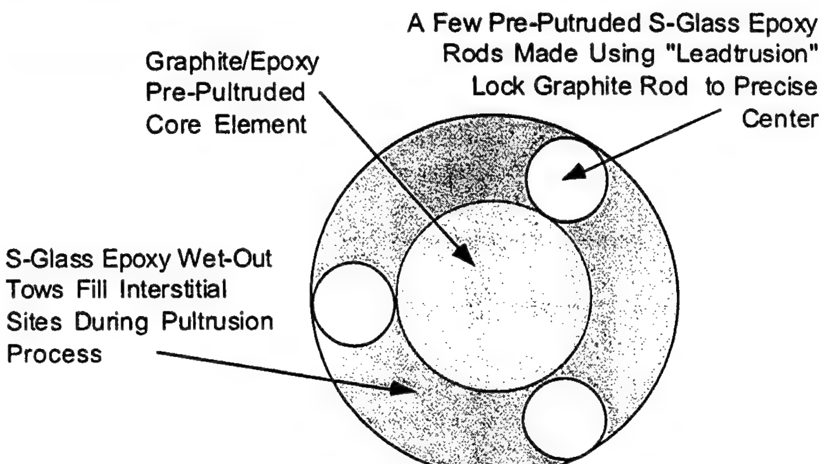
Integrated Structural Systems
Large Deployable Structures



Membrane Aerobrake



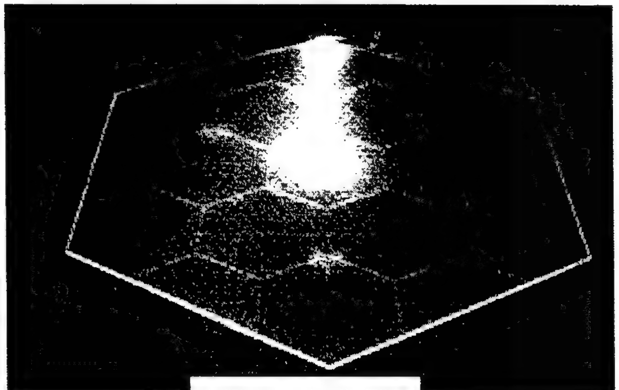
Integrally Hinged Structures



Pultrusion for Space Structures

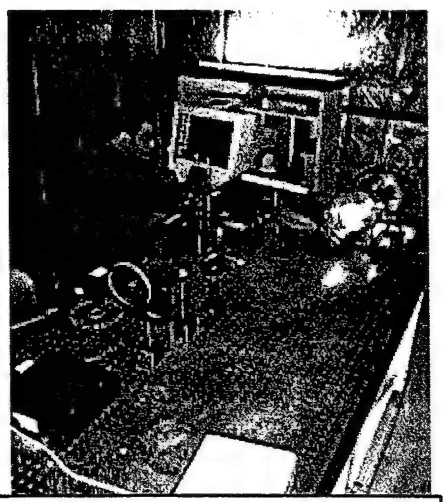
- Enable new ultra-large space system architectures
  - Membrane structures
  - Elastic Memory Composites (EMCs)
  - Pultruded booms
  - Stiffness critical structures

Integrated Structural Systems
Structures for Optical Systems



AMSD Mirror

Elastic Memory Composite

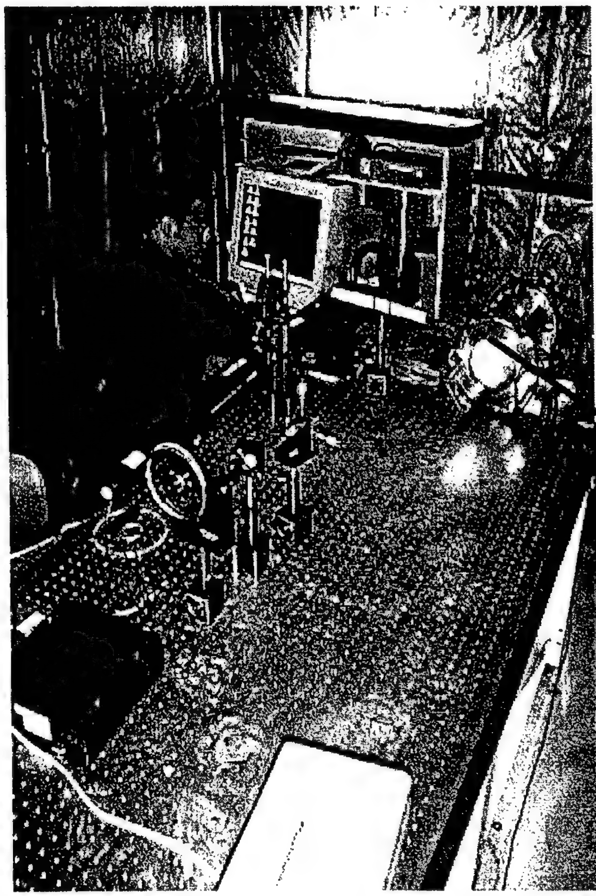


Active Membrane Structures

- Enabling technologies for space-based optical systems
  - Lightweight mirror structures
  - Active membrane optics
  - Stiffness critical joining
  - Rapid mirror fabrication

Electroactive Polymer for Membrane Optics
Experimental Measurement of Surface Change

LabView Based Interferometry
Software Development
6" Diameter Vacuum Chamber



* Apply epoxy to membrane and monitor surface shape change over 30 minutes to 4 hours.

Observed movement <0.2mm

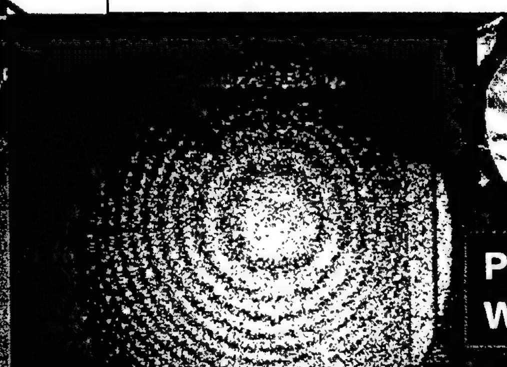
Analytically prediction supports observations

Vacuum loss interferes with test sensitivity

* Actuate PVDF (Electroactive) polymer

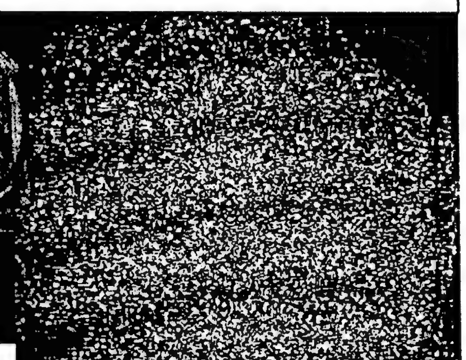
Micron (?10?) level movement monitored

Larger (mm level) movement not possible



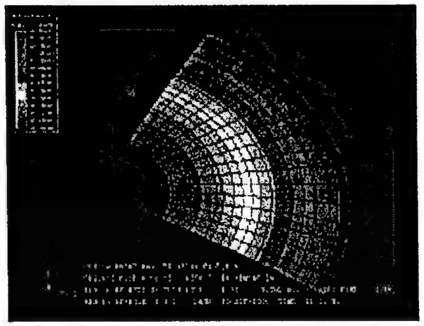
Initial Surface – Moire Interferometry

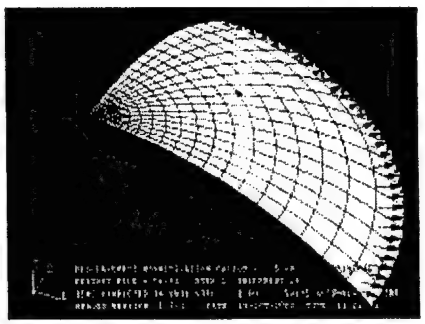
PVDF Film With Leads

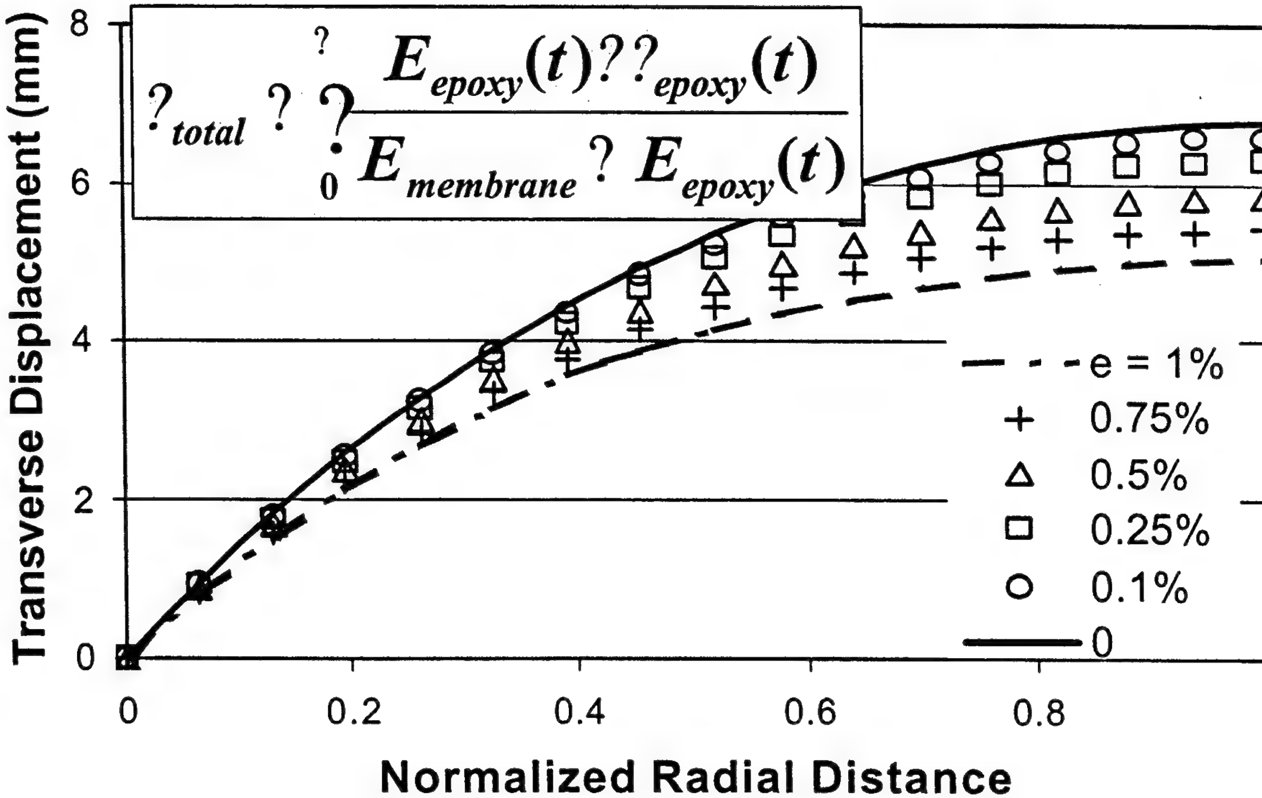


Surface Change- Shearography

Electroactive Polymer for Membrane Optics
Finite Element (ABAQUS) Analyses of Actuation





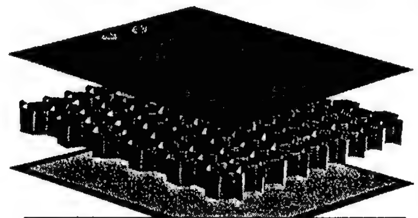


Conclusion:

Based on Analytical (FEM) results and available test data,
Possible shape correction is much less than the surface error!

Integrated Structural Systems
Multifunctional Structures

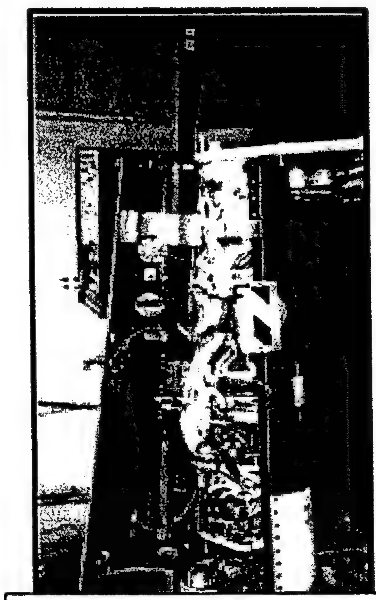
LightWeight Flexible Solar Arrays



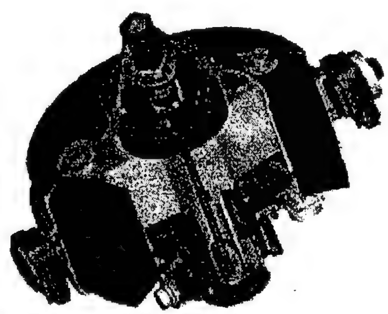
Integral Power Storage

Chassis Systems

Magnetostictive Materials



Launch Vehicle Systems



High-speed Rotors

- Revolutionary improvements in performance through multifunctional structures
  - Lightweight flex cabling
  - Miniaturized electronics
  - Flywheel rotors for energy storage and attitude control
  - Materials with high passive damping
  - Energy storage materials/structures

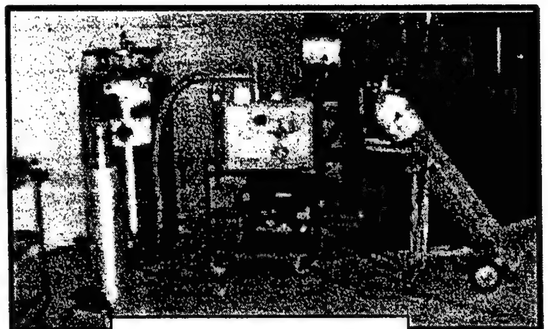
Self Consuming Satellite
Objectives/Background

- Investigate the material properties of Tefzel (fuel for PPT) with Kevlar whiskers reinforcement
- Variables to be investigated:
  - Fabrication techniques
  - Number of layers in lamination construction
  - Fiber contents
  - Fiber forms

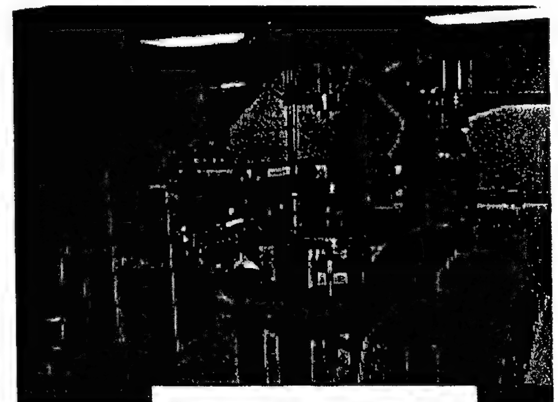
Tensile specimen mold

Integrated Structural Systems
Innovative Concepts

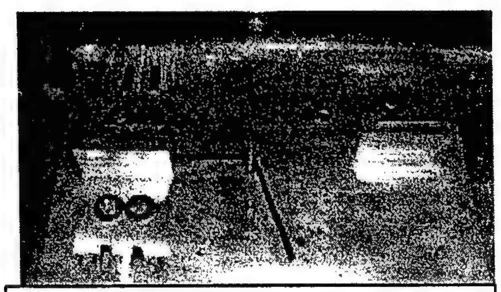
Electrically Disbonding Adhesive



Cryo Test Facility



Biaxial Test Facility

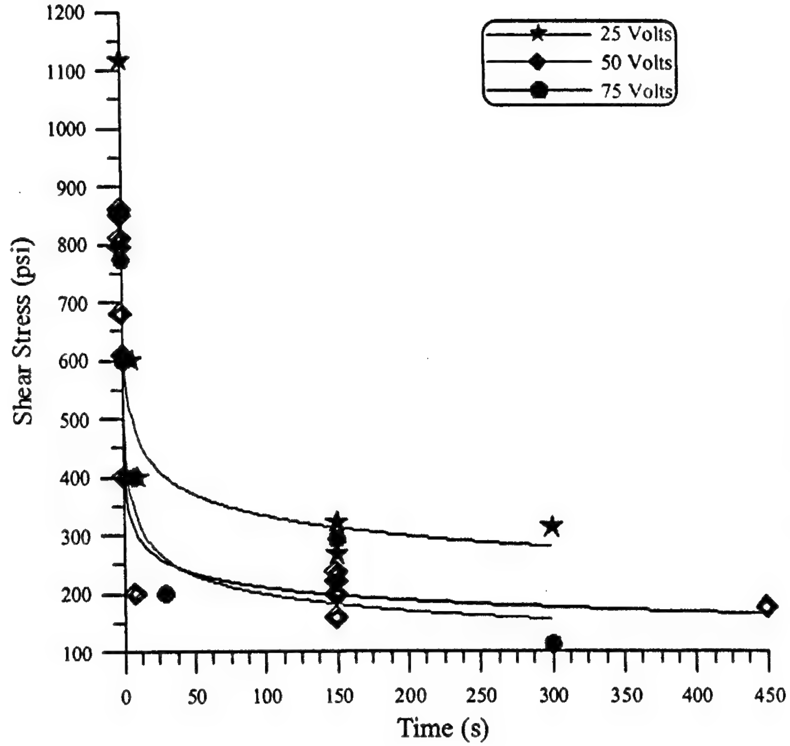


Deployment of Elastic Memory Composite

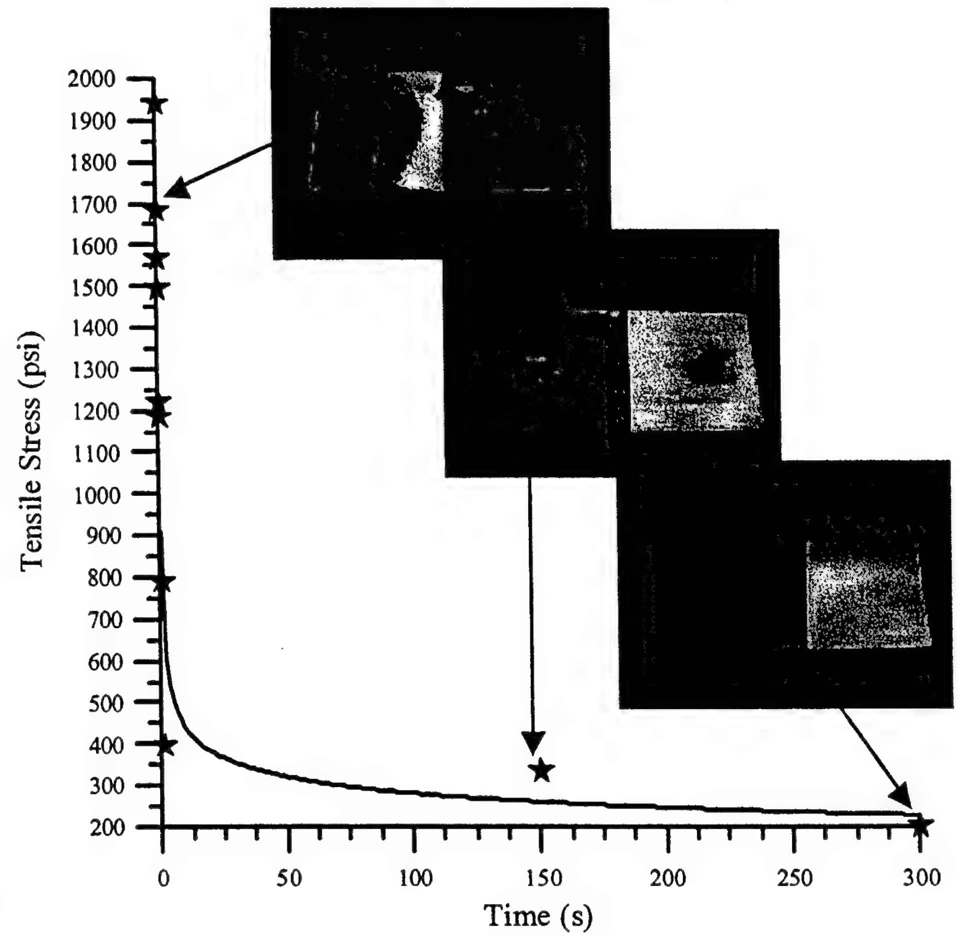
- **Basic research provides the seeds to enable generation + 2 systems**
  - **Electrically disbonding adhesives**
  - **Elastic memory composites**
  - **Multiaxial testing of composites**
  - **Self healing composite materials**

Electrically Dis-Bonding Epoxy
Results

ElectRelease Lap Shear Stress:
6061-T6 Aluminum Substrate



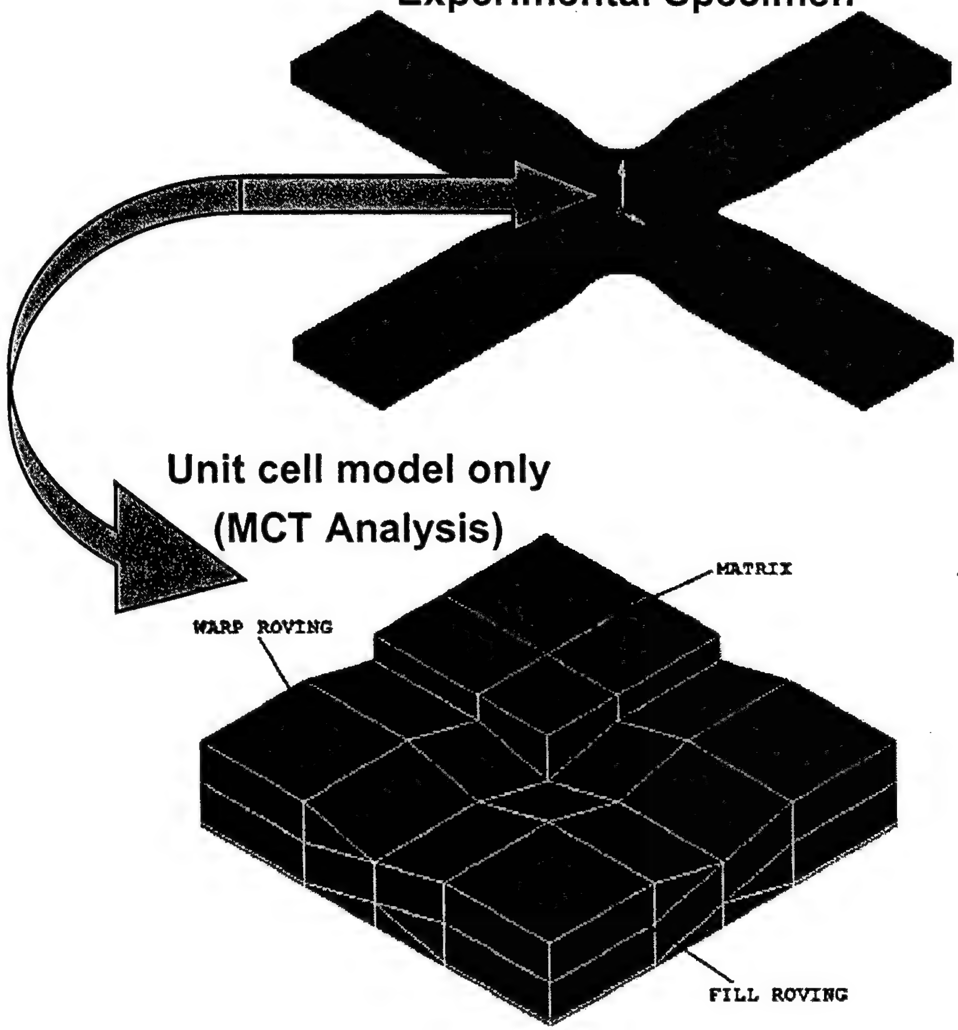
ElectRelease Tensile Stress:
6061-T6 Aluminum Substrate @ 75V



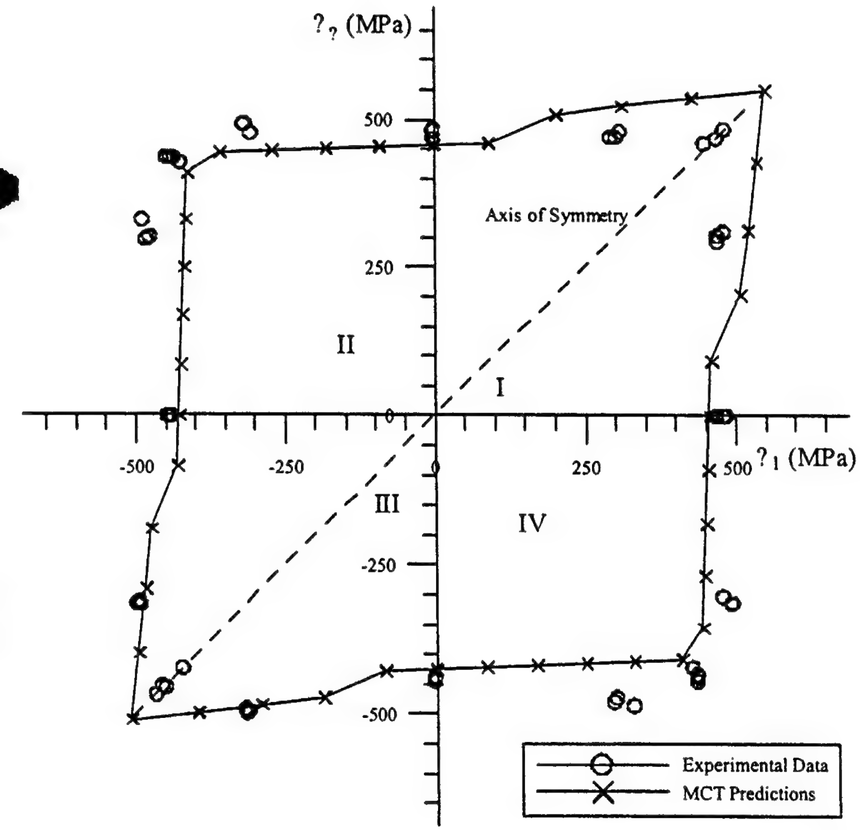
Dis-bond time affects failure mode of adhesive

Biaxial Testing of Composite Laminates
Results

Experimental Specimen



18-oz Biased (5 warp/4 fill rovings)
Plain Weave E-Glass/Vinyl Ester
Cross-ply Laminate

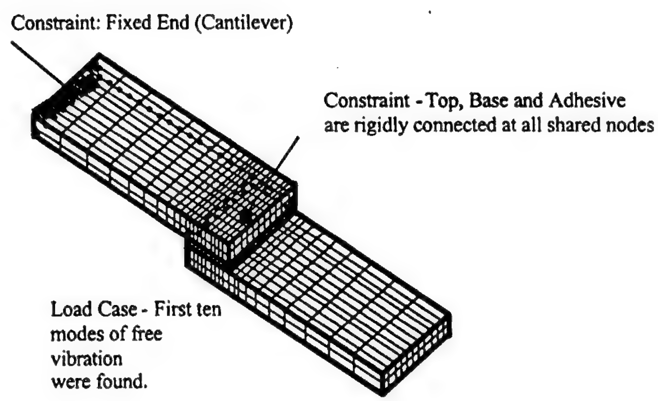


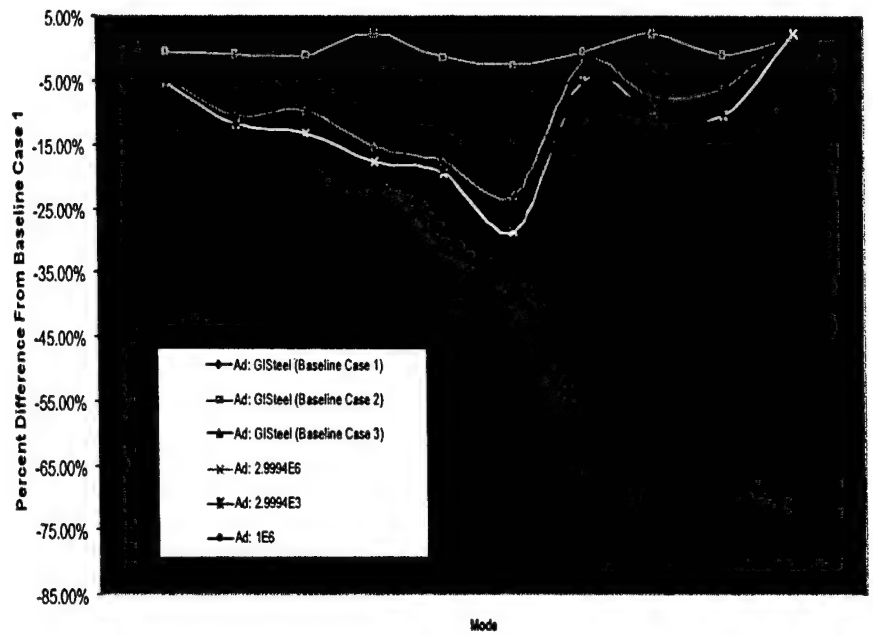
Close agreement between numerical predictions and experimental data!

Stiffness Critical Composite Joining

Results

- Step 1 – Predict static stiffness of lap-shear joint
  - Compare numerical model to experiment

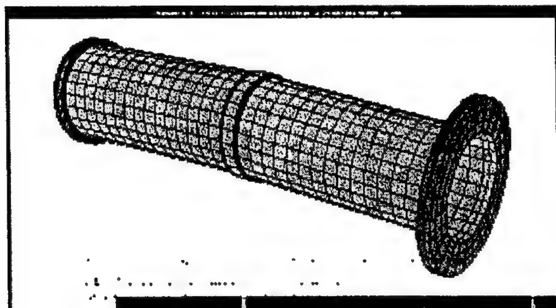


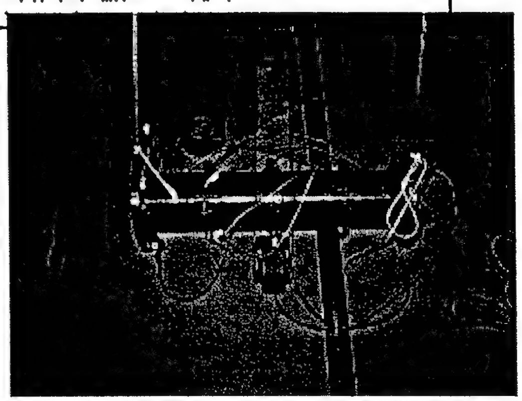


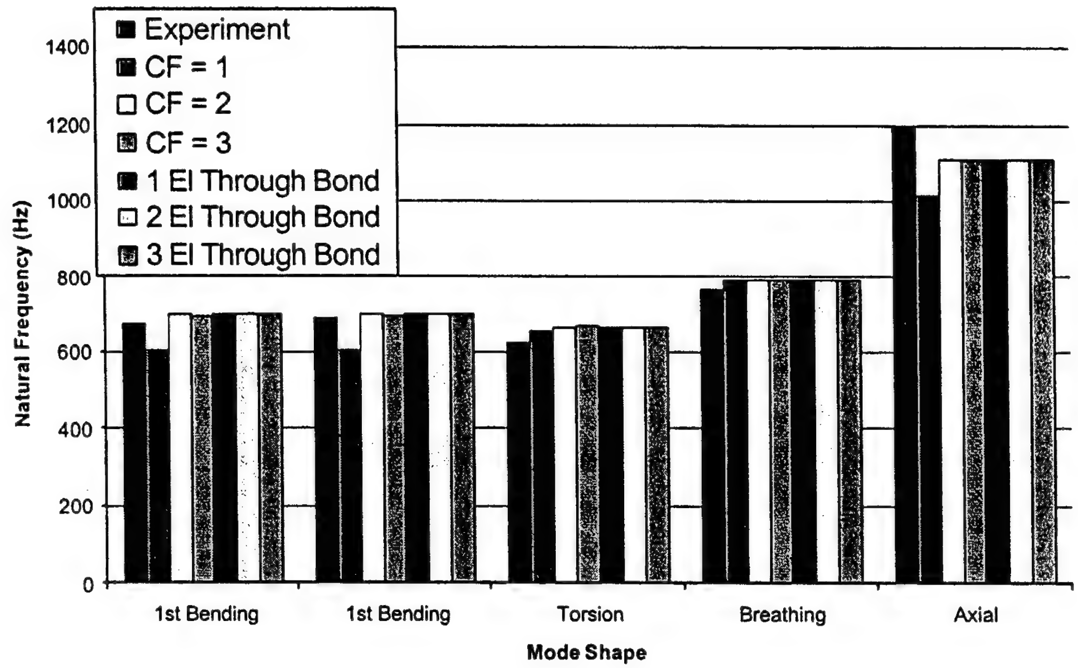
- Results
  - Neglecting the adhesive bond results in errors > 25%
  - One element through the thickness captures the dynamic behavior (3D brick element with nonlinear material properties)

Stiffness Critical Composite Joining
Results

- Step 2 – Predict behavior of dynamic test article
  - Compare numerical model to experiment



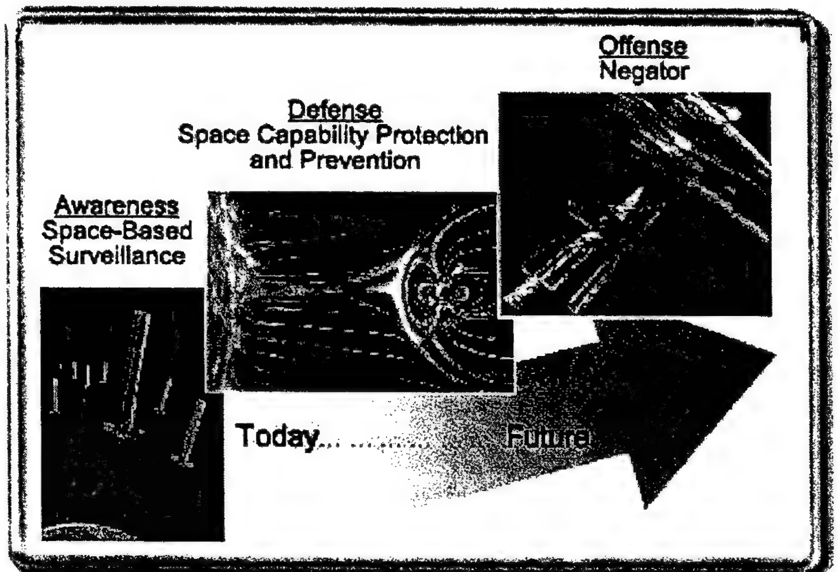




- Results
  - FE model can predict performance for first 6 modes
  - Higher modes not measured due to experimental setup

Conclusions

- **AFOSR support is vital to AFRL/VSSV programs.**



1st Multifunctional Aerospace Materials Workshop

Purdue University

23-24 October 2002

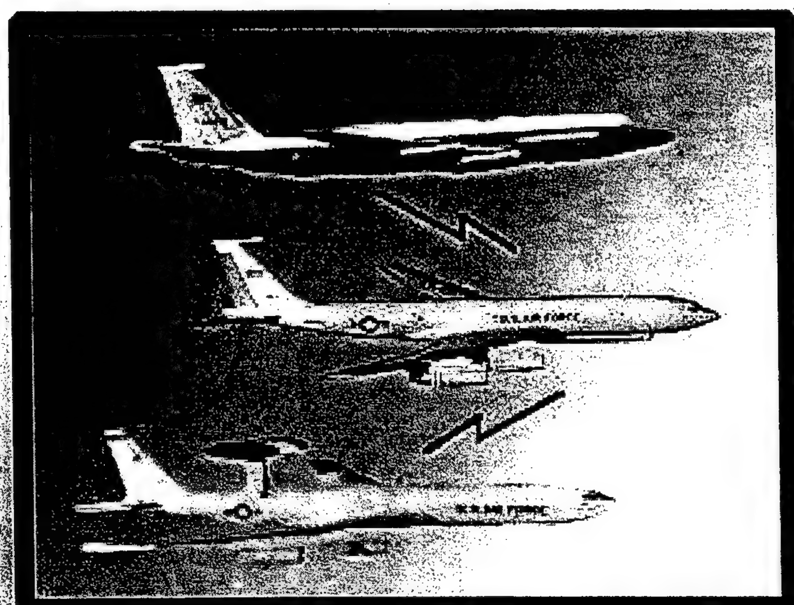
Conformal Load-Bearing Antenna Structures (CLAS)

William G. Baron
AFRL/VAS
Joe Tenbarge
AFRL/SNR

Critical ISR Needs Not Met with Todays Systems

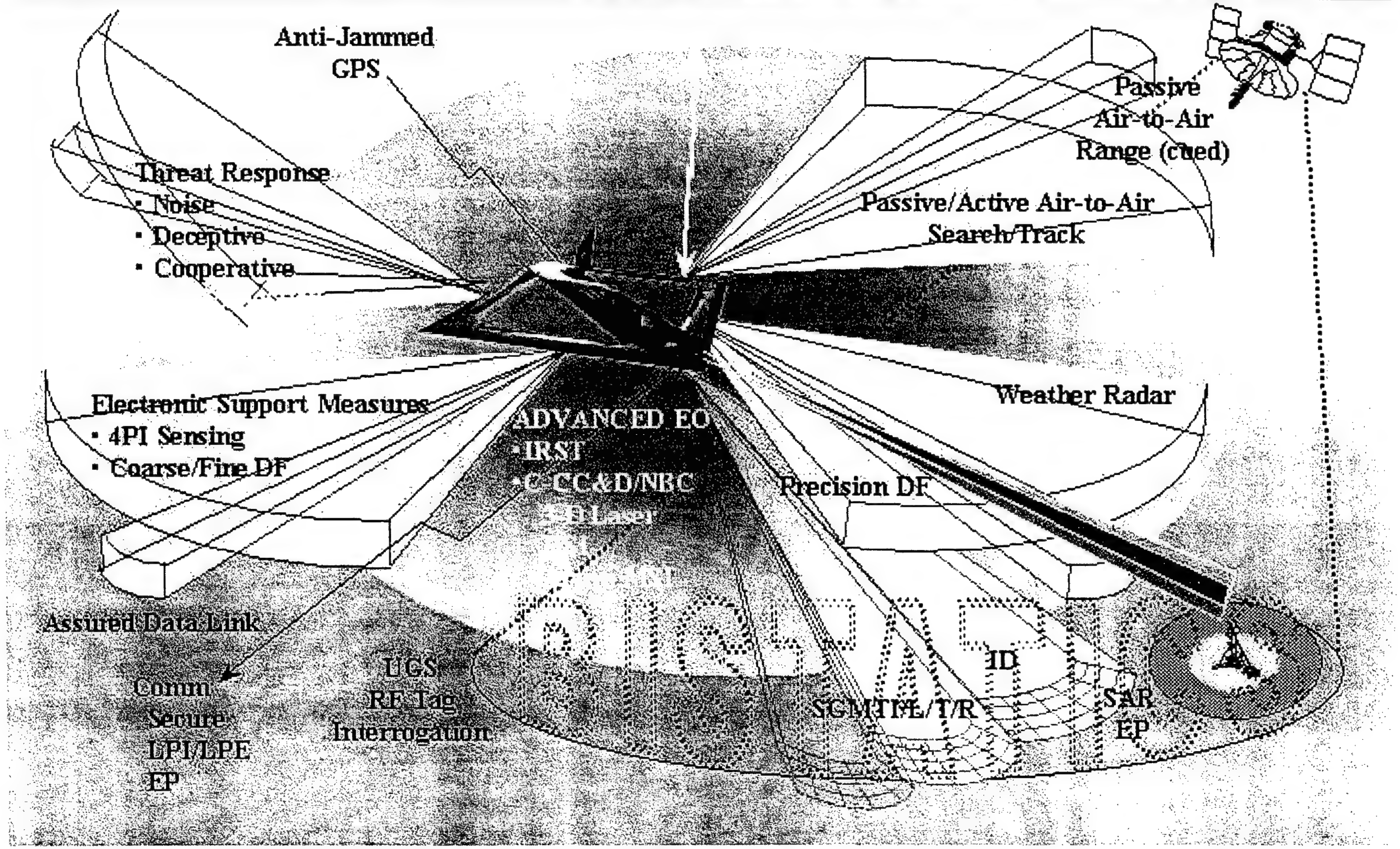
Long Range Positive Detection, Identification, Tracking and Targeting

Critical Manpower Shortages, Aging Systems, and Significant Infrastructure Costs Associated with ISR



Sensorcraft Functionality

& Space Interdependence



Sensorcraft Cost and Weight Challenges

X-Band aperture (20 ft x 1.5 ft):

Current technology

- cost
  - $\$300K/ft^2 \times 30\ ft^2 = \$9M/array$
  - $9M x 4 arrays = *$36M*
- weight
  - $35lbs/ft^2 \times 30\ ft^2 =$ 1050lbs/array
  - 1050lbs x 4 arrays = *4200lbs*

Low-Band (>40 ft – freq. dependent):

Current technology (UHF)

- Size – significant volume required array elements (>18 inches deep)
- weight
  - 800lbs/array (antenna only)
  - 800lbs/array x 4 arrays = *3200lbs*

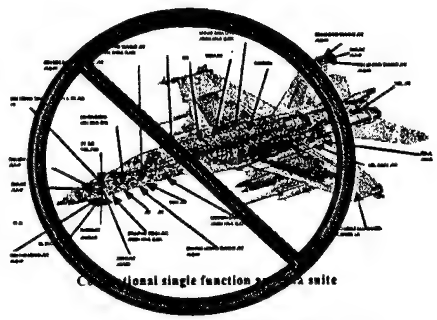
Significant cost, volume and weight savings required

RF-on-Flex

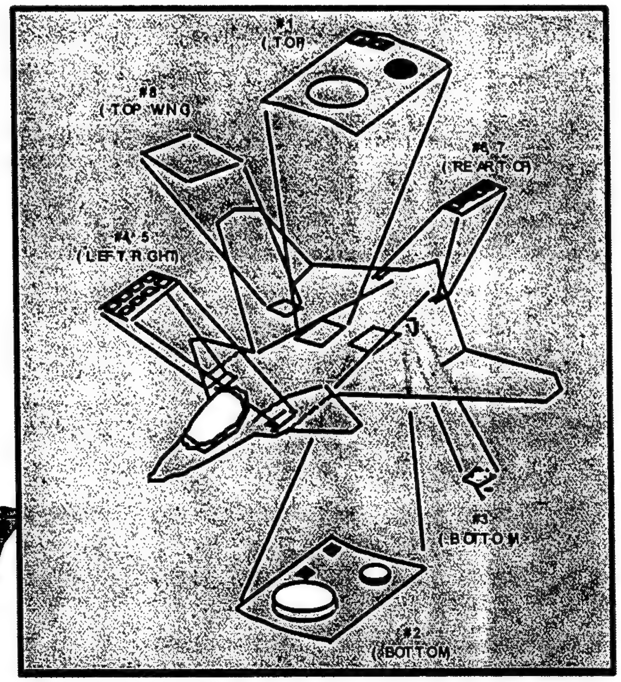
Conformal Load Bearing Arrays

Conformal Load Bearing Antenna Structure (CLAS)

Non load bearing cavity installations require support structure adding weight & cost



SOLUTION

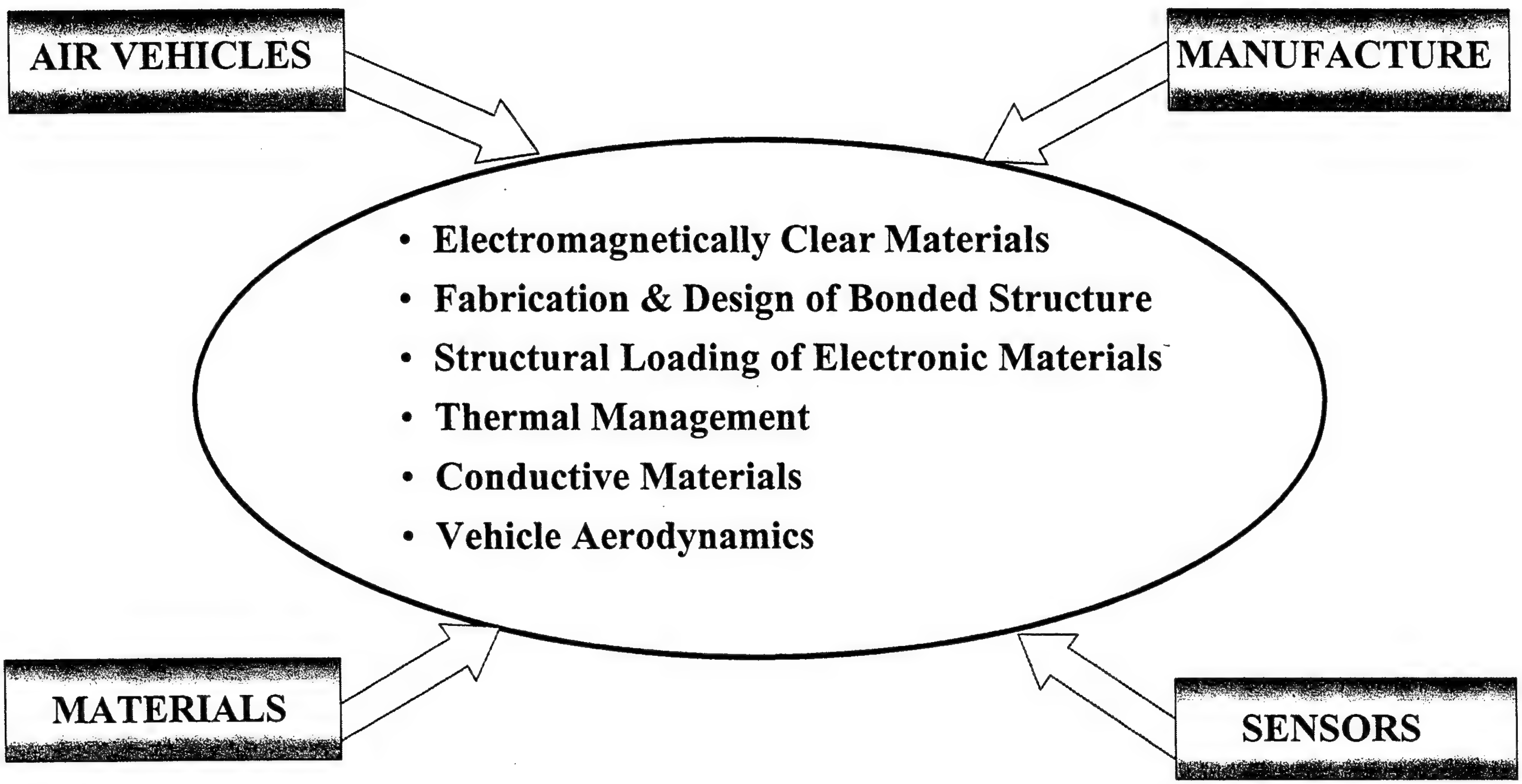


- Integrate antenna function into the structure
- Antenna structure is load bearing
- LO enabling
- Reduced maintenance vulnerability

PAYOFFS

- Enhanced Antenna Performance by Exploiting Skin Acreage
- Improved Aerodynamics and Structural Efficiency

Multidisciplinary Antenna Integration Challenges

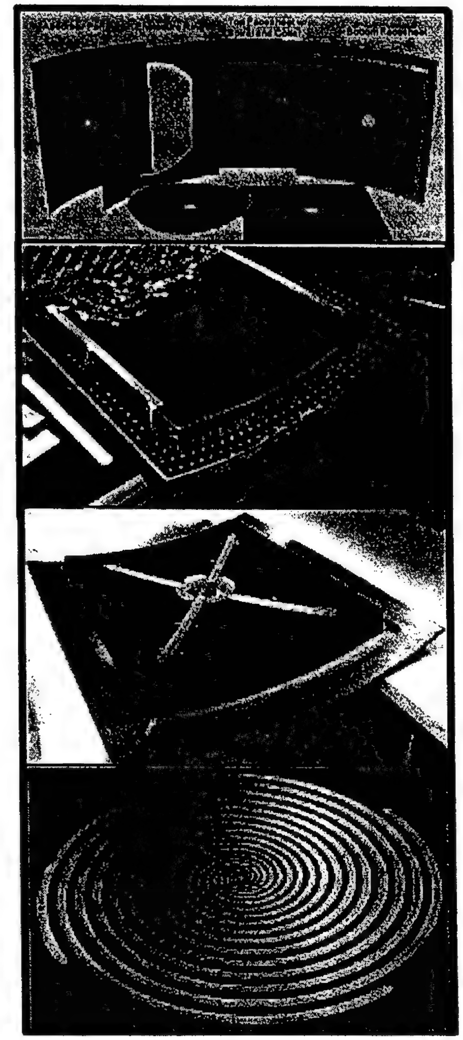


Wide Band Spiral Antenna Comm/Nav

Fuselage Panel

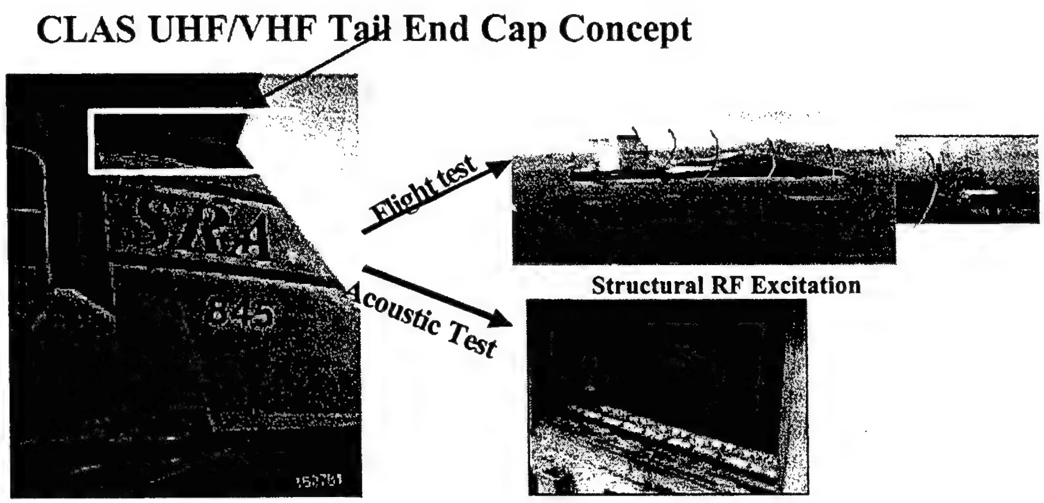
Designed, Developed & Tested a Conformal, Load-Bearing, Multifunction (0.15 - 2.0 GHz) Antenna

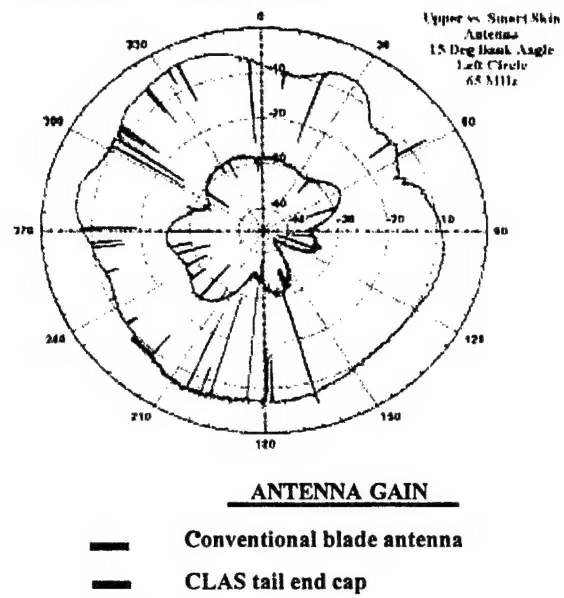
- **The First and Largest Multifunction, Conformal, Load-Bearing, Spiral Antenna Built for Airborne Application**
- **Eliminates up to 10 Comm/Nav Elements**
- **Spiral Element Developed by SN**
- **Combined-Load Fatigue Testing**
- **Spinning Linear Mode Testing**



Communication Element Development

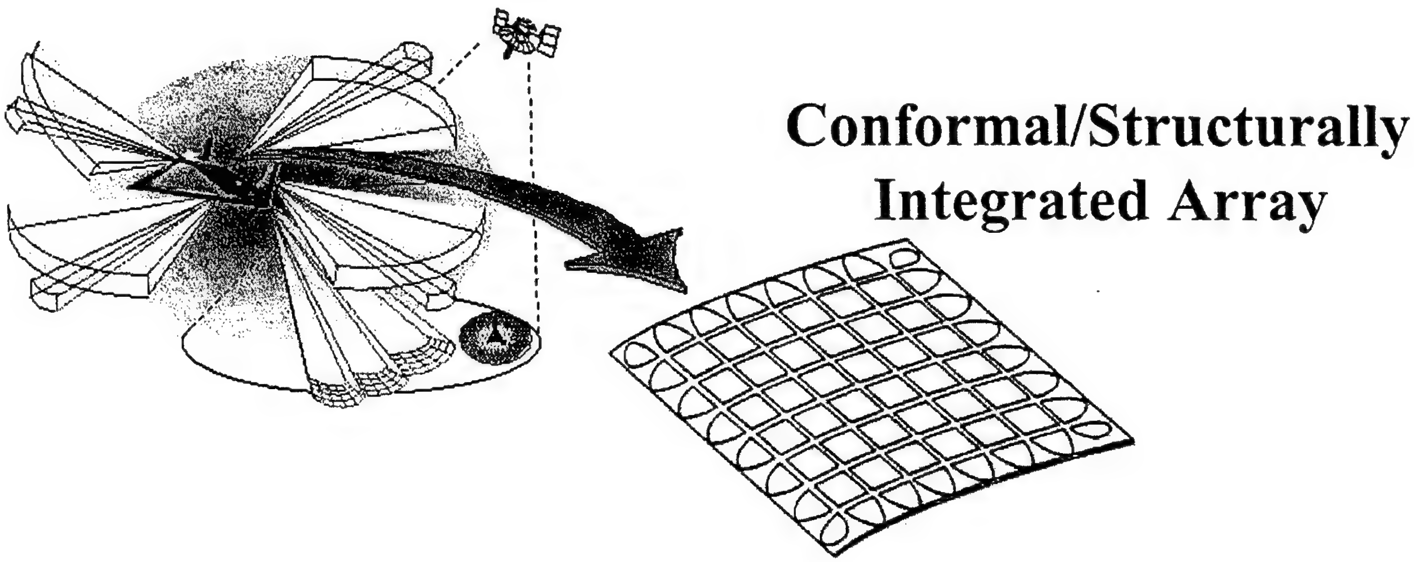
Goal: Replace Conventional Blade Antennas with End Cap with no Degradation in Performance





- Blade Antennas not suitable for LO and subject to damage
- The CLAS end cap was flight tested with dramatic gain improvement results, as shown in the gain vs azimuth plot
- The CLAS end cap increased VHF voice communication range 17 fold

Structurally Integrated Phased Arrays Development Focus



- Low & High Frequency Array Development
- Deformation Sensing for Beam-Forming
- Low Cost Flexible Electronics
- Design for Repair/Graceful Degradation
- Bonded Structure

Multifunctional Material Research Needs

- **Deformation sensing**
  - Sensor integ & development, ingress/egress, algorithm development
- **Conductor development**
  - Nano based conductive polymers
  - Conductive fiber
  - Electroless reel to reel plating
- **Integrated thermal management**
  - High thermal conductivity tailored material
  - Heat exchanger/heat pipe solutions for integrated electronics
- **Electrical distribution – data/power**
  - Direct write, thin films, co-cured conduits & conductors
  - Self healing electrical conductors
  - Bonding of conductors
- **Dielectric material development**
  - Voltage breakdown strength
  - Nano particle dispersion for high dielectric constant polymers
  - High strength/stiffness dielectric polymers
  - Tunable dielectrics for broadband performance

1st Air Force Workshop on
Multifunctional Aerospace Materials

Design Issues for Multifunctional Materials and Structures

J. P. Thomas, M. A. Qidwai, and P. Matic
Multifunctional Materials Branch, Code 6350
Naval Research Laboratory
Washington, DC

Acknowledgements: Support for this work from Defense Advanced Research Projects Agency and Naval Research Laboratory Core Research Program is gratefully acknowledged.

Purdue University, West Lafayette, IN
October 23, 2002

Multifunctional Structure-Power Materials

DARPA PROGRAM GOALS: Develop design strategies, analysis methods, performance indices, and UAV component prototypes for three multifunctional structure-power concepts.

Concept #1:	**Multifunctional structure-battery** -- Telcordia's Plastic-Lithium-Ion battery as UAV structure.
Concept #2:	**Autophagous structure-fuel** – UAV structural elements that transform into propulsion fuel.
Concept #3:	**Variform structure-power** -- pressurized fuel structural elements for morphing UAV's.

Industry Partners

M. Keennon and J. Asplund
AeroVironment, Inc.
Design Development Center
Simi Valley, CA

A. DuPasquier
Telcordia Technologies, Inc.
Energy Storage Research
Red Bank, NJ

AeroVironment Inc.

Telcordia Technologies
Formerly Bellcore...
Performance from Experience

What's Possible with Structure-Power ??

Empirical Aircraft Weight Data

	Weights						Str. Wgt.	Fuel Wgt.
Micro	Total		Structure	Fuel	Propulsion	Payload	Total Wgt.	Total Wgt.
Black Widow (AeroVironment)	81	gms.	9	41.1	17.5	13.4	0.111	0.507
Microstar (Lockheed-Martin)	85	gms.	7	44.5	13.5	20	0.082	0.524
Unmanned								
Dragon Eye (NRL)	4	lbs.	0.5	1.5	1	1	0.125	0.375
Pointer (AeroVironment)*	9.2	lbs.	4	2.2	1	2	0.435	0.239
Sender (NRL)	10	lbs.	4	3	1	2	0.400	0.300
LOCAAS (Lockheed-Martin)	85	lbs.	51	10	7	17	0.600	0.118
Shadow 200 (AAI)	328	lbs.	179	63	26	60	0.546	0.192
Predator (General Atomics)	2250	lbs.	1,013	650	137	450	0.450	0.289
Darkstar (L-M/Boeing)	8,600	lbs.	4,107	2960	452	1081	0.478	0.344
Conventional								
F/A-18 (Boeing)	56,000	lbs.	19,268	15,000	4,564	17,168	0.344	0.268
F-16C (Lockheed-Martin)	42,300	lbs.	14,977	14,234	3,940	9,149	0.354	0.337
F-14D (Grumman)	74,349	lbs.	34,730	19,557	7,050	13,012	0.467	0.263
777-200 (Boeing)	545,000	lbs.	195,072	207,700	33,328	108,900	0.358	0.381
767-300ER (Boeing)	380,000	lbs.	103,262	162,340	18,998	95,400	0.272	0.427
747-200B (Boeing)	785,000	lbs.	233,260	364,400	35,540	151,800	0.297	0.464
737-900A (Boeing)	164,000	lbs.	62,805	46,063	10,512	44,620	0.383	0.281
MD-11 (Boeing)	602,555	lbs.	202,302	258,721	28,497	113,035	0.336	0.429
A320-200 (Airbus)	162,040	lbs.	57,054	52,495	10,826	41,665	0.352	0.324
A340-600 (Airbus)	804,675	lbs.	299,103	344,936	21,976	138,660	0.372	0.429

References: Janes "All the World's Aircraft", "Unmanned Aerial Vehicles ...", "Aero-Engines", and unpublished data.

Average=	**0.369**	**0.340**
Std.Dev.=	**0.129**	**0.109**

Battery-Powered

Liquid-Fuel Powered

Variform Structure-Fuel

Morphing Aircraft with Liquid Fuel as Structure !!

System Optimization

UAV Flight Endurance Time

Structure-Power Multifunctionality

$$E_E(time) = \overbrace{\frac{E_B \times \eta_B}{\underbrace{\left(W_S + W_B + W_{PR} + W_{PL} + W_{SB}\right)^{3/2}}_{\text{Total Weight}}}}^{\text{Available Battery Energy}} \times \underbrace{\left[\frac{\rho S C_L^3}{2 C_D^2}\right]^{1/2}}_{\text{Aerodynamics, Geometry}} \times \underbrace{\eta_P}_{\text{Propeller Efficiency}}$$

$$\boxed{\frac{\Delta E_E}{E_E} = \frac{\Delta\left(E_B \eta_B\right)}{E_B \eta_B} - \frac{3}{2}\frac{\left(\Delta W_S + \Delta W_B + \Delta W_{SB}\right)}{W_{total}}}$$

Complication:

$$\eta_B = \eta_B\left(E_B, W_{total}\right)$$

$$\eta_P = \eta_P\left(W_{total}\right)$$

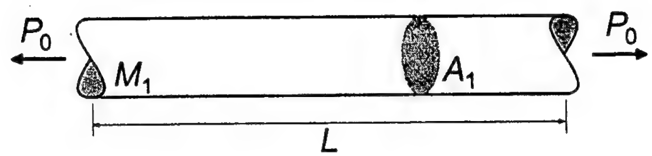
→ System-Level Multidisciplinary Design Optimization Required !!!

Unifunctional Materials Performance

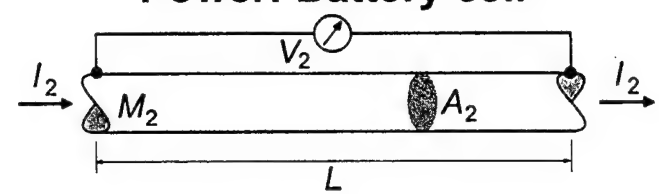
Design Objective: minimize the system weight

I. Unifunctional Design: Structure and Power Functions

Structure: Axial Tie



Power: Battery cell



$m_1 = \rho_1 A_1 L$:component weights: $m_2 = \rho_2 A_2 L$

M1 constraint: stress ≤ strength

$$\sigma_1 = P_0 / A_1 \le \underbrace{(\sigma_Y)_1}_{\text{yield strength}} \Rightarrow m_1 \ge P_0 L \left\{ \rho_1 / (\sigma_Y)_1 \right\}$$

M2 constraint: total stored energy ≥ constant, E_0

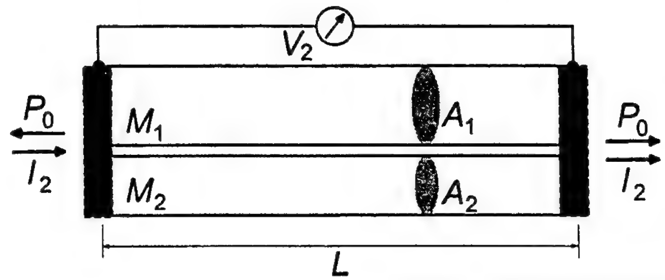
$$E_2 = m_2 \times \underbrace{(e_B)_2}_{\text{specific energy}} \ge E_0 \Rightarrow m_2 = E_0 \left\{ 1 / (e_B)_2 \right\}$$

total unifunctional system weight, $(m_T)_u = m_1 + m_2$

$$\boxed{(m_T)_u = P_0 L \left\{ \rho_1 / (\sigma_Y)_1 \right\} + E_0 \left\{ 1 / (e_B)_2 \right\}}$$

Multifunctional Materials Performance

II. Multifunctional Design: Structure-Battery Function



System constraints:

$$\delta_1 = \delta_2 = \delta_T = \frac{P_1 L}{A_1 E_1} = \frac{P_2 L}{A_2 E_2}$$

$$P_0 = P_1 + P_2$$

Total multifunctional system weight, $(m_T)_m$

$$(m_T)_m = m_1 + m_2 = (\rho_1 A_1 + \rho_2 A_2)L$$

Case 1: $\dfrac{(\sigma_Y)_2}{\rho_2} \geq \dfrac{(\sigma_Y)_1}{\rho_1} \Rightarrow$ Eliminate M_1, replace with M_2 structure-battery!!

1a: $\boxed{(m_T)_m = E_0 \left\{ 1/(e_B)_2 \right\} << (m_T)_u}$

$E_2 = m_2 \times (e_B)_2 = E_0$ and $\sigma_2 = P_2/A_2 \leq (\sigma_Y)_2$

1b: $\boxed{(m_T)_m = P_0 l \left\{ \rho_2/(\sigma_Y)_2 \right\} << (m_T)_u}$

$\sigma_2 = P_2/A_2 = (\sigma_Y)_2$ and $E_2 = m_2 \times (e_B)_2 \geq E_0$

Multifunctional Materials Performance

Case 2: $\frac{(\sigma_Y)_1}{\rho_1} > \frac{(\sigma_Y)_2}{\rho_2} \Rightarrow$ M_1 structure plus M_2 structure-battery!!

2a:

$$\underbrace{(m_T)_m}_{\text{unifunctional system weight}} = (m_T)_u - E_0 \left\{ \frac{1}{(e_B)_2} \right\} \times \left\{ \frac{E_2/\rho_2}{E_1/\rho_1} \right\} < (m_T)_u$$

$$\sigma_1 = P_1/A_1 = (\sigma_Y)_1, \quad E_2 = m_2 \times (e_B)_2 = E_0, \quad \text{and} \quad \sigma_2 = P_2/A_2 \leq (\sigma_Y)_2$$

2b:

$$\underbrace{(m_T)_m}_{\text{unifunctional system weight}} = (m_T)_u - E_0 \left\{ \frac{1}{(e_B)_2} \right\} \times \left\{ \frac{E_2/\rho_2}{E_1/\rho_1} \right\} + \rho_1 \left\{ \frac{(\sigma_Y)_1 - (\sigma_Y)_2}{(\sigma_Y)_1 (\sigma_Y)_1} \right\} P_0 l < (m_T)_u$$

$$\sigma_2 = P_2/A_2 = (\sigma_Y)_2, \quad E_2 = m_2 \times (e_B)_2 = E_0, \quad \text{and} \quad \sigma_1 = P_1/A_1 \leq (\sigma_Y)_1$$

Important Conclusions:

1. System weight ***always less*** using multifunctional material design!
2. System optimization generally occurs with "non-optimal" subsystem designs.
3. Multifunctional performance ranking: **1a** or **1b**, **2a**, then **2b**.

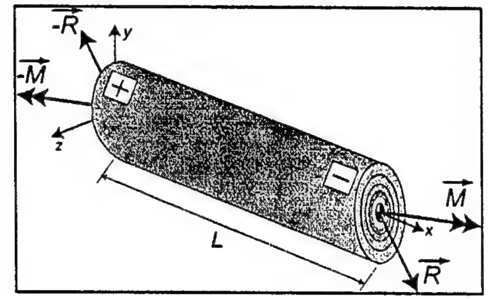
Mechanical Performance Indices

Minimal Axial Displacement and Weight → **Maximize Specific Axial Stiffness**

Axial Displacement: $\delta = \dfrac{PL}{E_R A^*}$ $\qquad A^* := \sum_{i=1}^{n} \dfrac{E_i}{E_R} A_i$

Axial Stiffness: $k_a := \dfrac{E_R A^*}{L}$ $\qquad$ Composite Property

Mass Density: $\rho := \sum_{i=1}^{n} \rho_i A_i$ $\qquad$ Composite Property



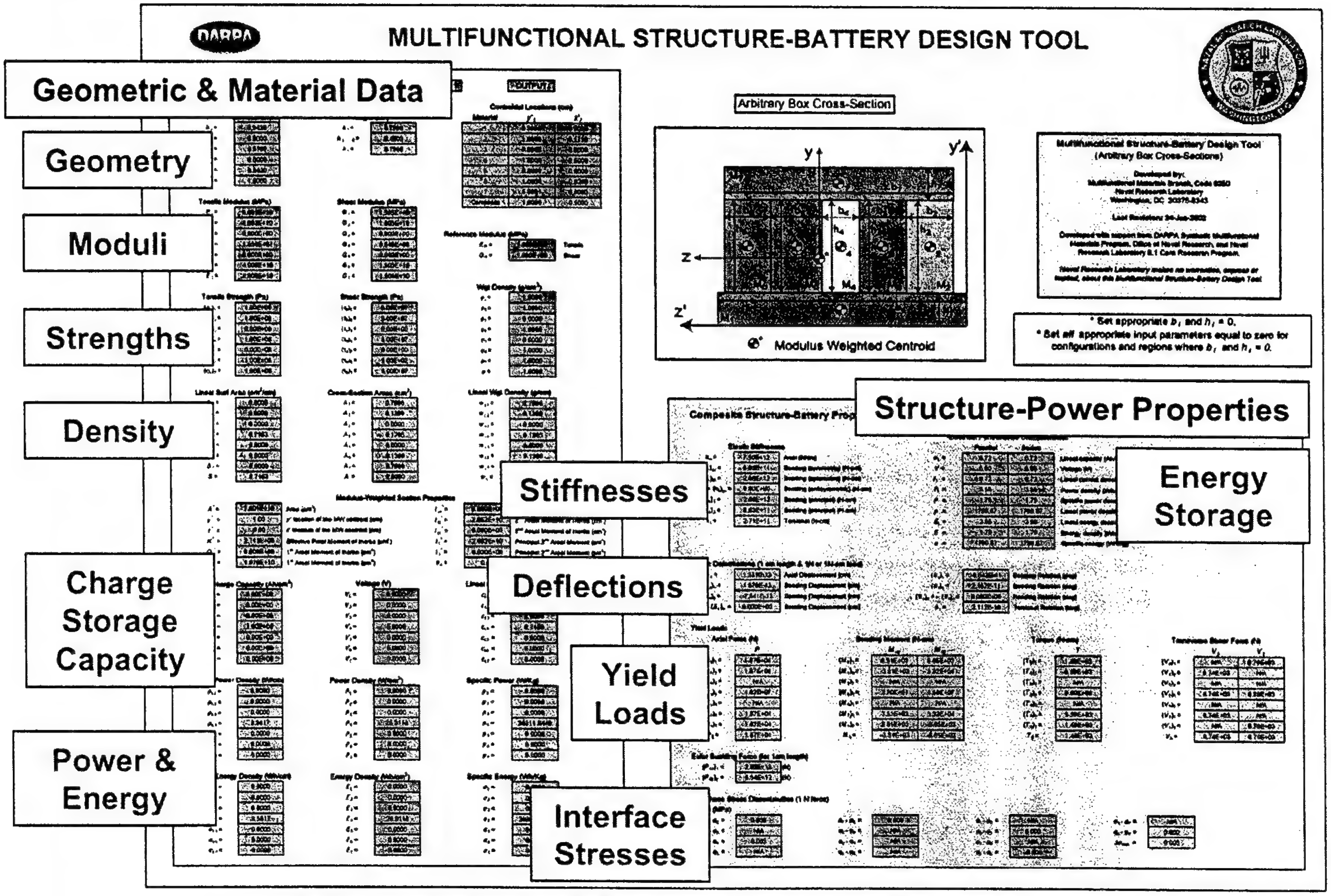
Specific Axial Stiffness: $p_a := \dfrac{k_a \times L}{\rho} = \dfrac{\sum_{i=1}^{n} E_i A_i}{\sum_{i=1}^{n} \rho_i A_i} = \dfrac{E}{\rho}$

Unifunctional

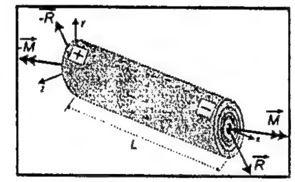
Multifunctional

Multifunctional Composite Performance Indices generally depend on the **constituent material properties, shapes,** and **location** within the cross-section .

Structure-Battery Design Tool (SBDT)

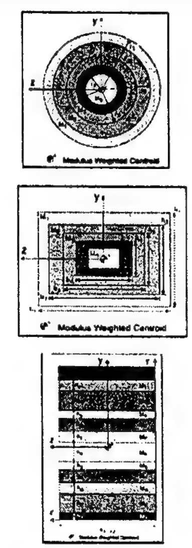


S-P Beam Materials



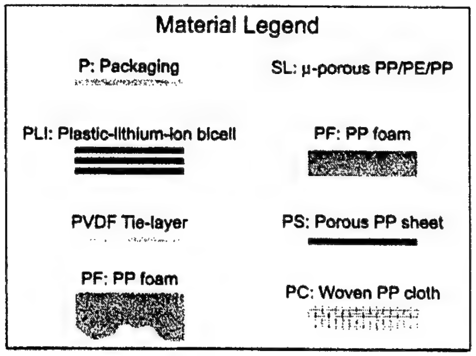
Tension, bending, torsion, shear, and buckling loading

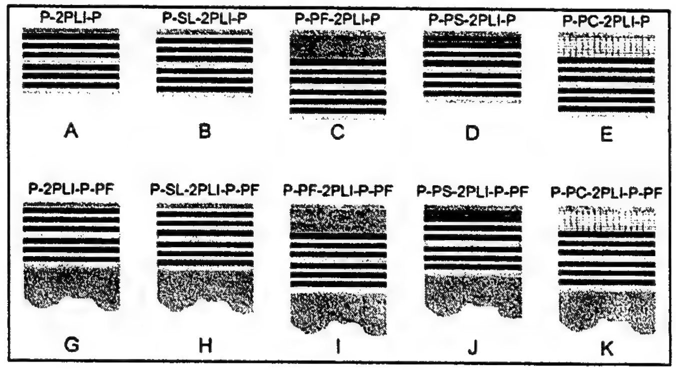
Other C-Sections

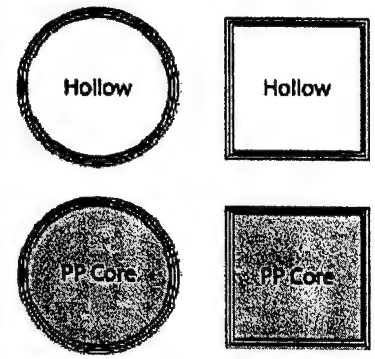


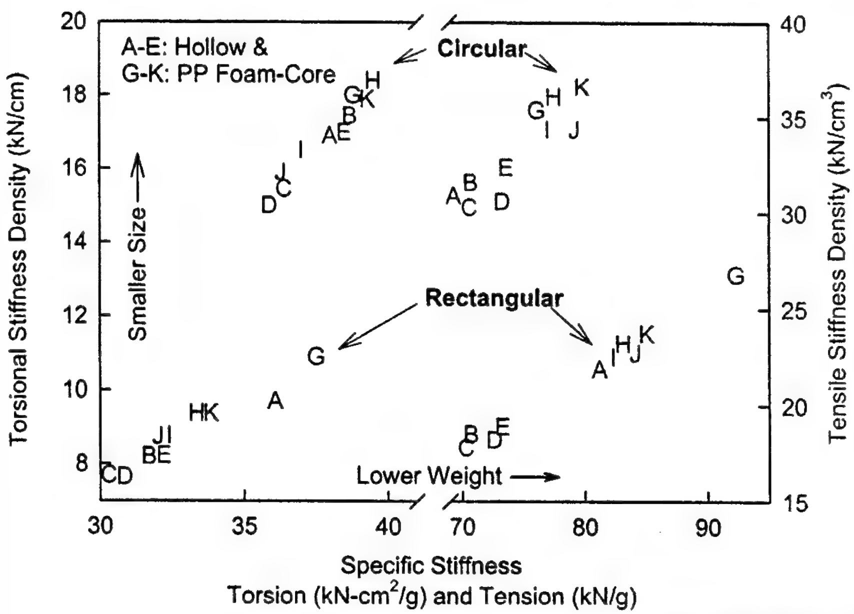
SBDT is adaptable to analyze any structure-power performance

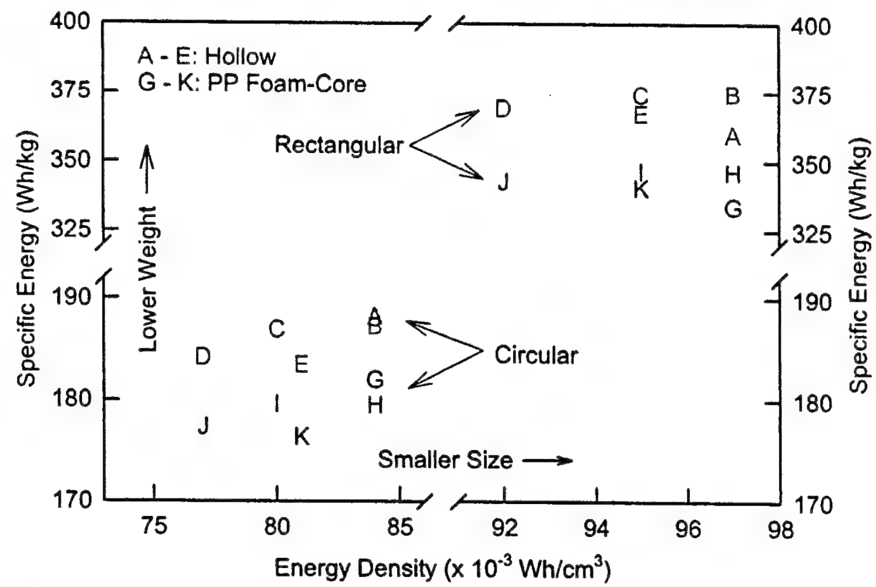
SBDT Study: Structure-PLI Struts







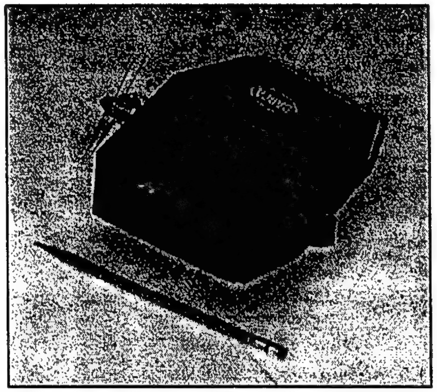




Useful Design Ranking Information!

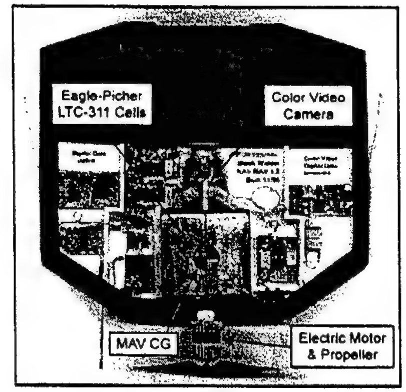
Structure-Battery for UAV's

Black-Widow Micro-Air-Vehicle

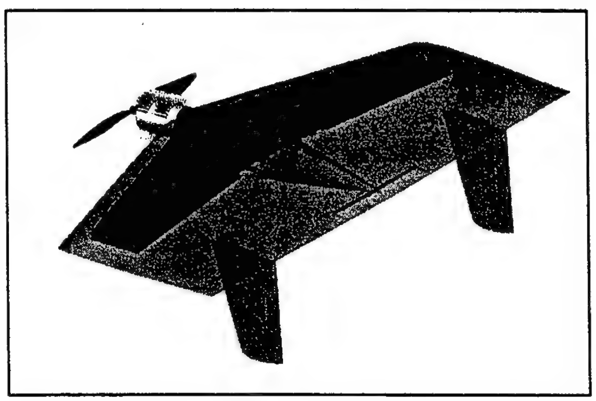


Capabilities

- 6" wing span
- 81 g weight
- **30 min. endurance**

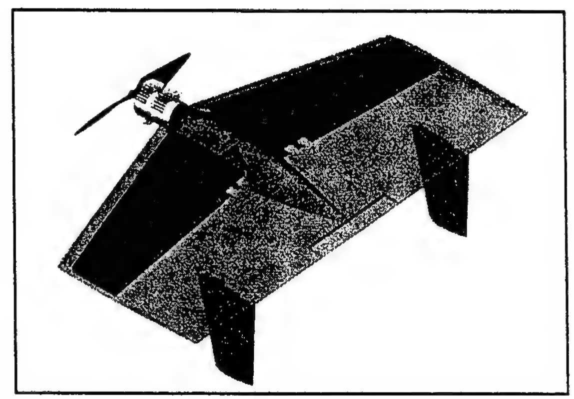


New Multifunctional Unmanned-Air-Vehicle



Design Goals

- 12" wing span
- 170 g weight
- **70+ min. endurance**



Structure-Battery Design for UAV's

Desirable Features

- High energy density and specific energy
- Arbitrary shaping capability
- Durability in flight, field, and storage
- Reliability
- Safe-failure modes

Multiple-Mission UAV's

- Rechargeability of the structure-battery → secondary cells or easily removed primary cells

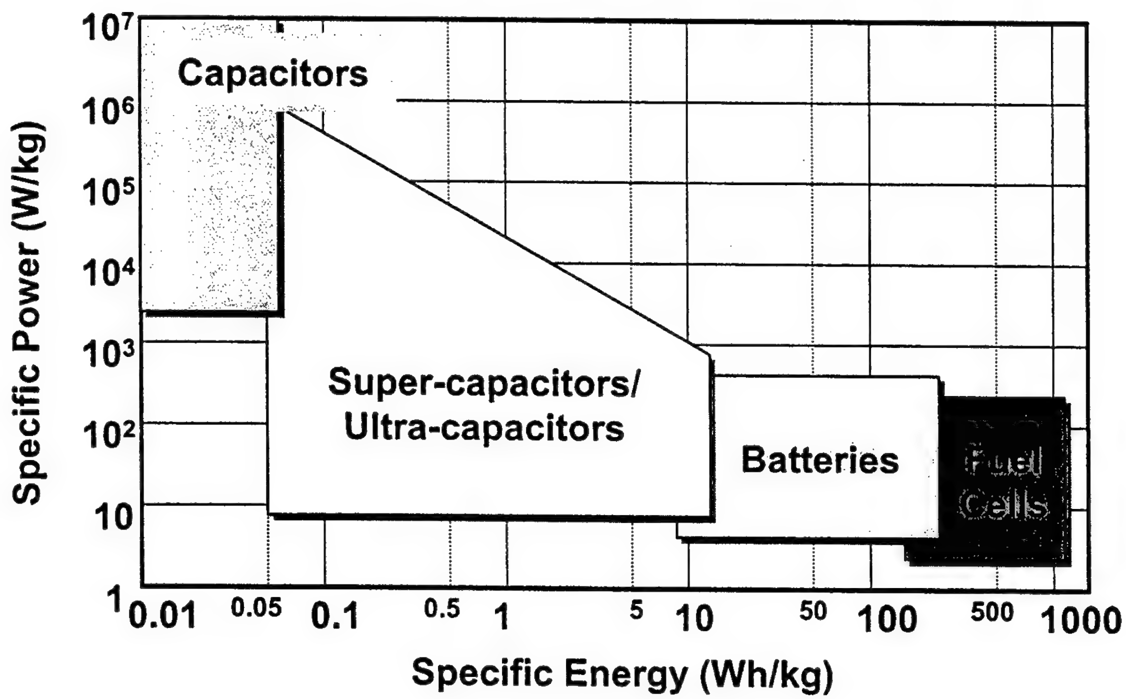
Single-Mission UAV's

- Low Cost

Multifunctional Design Rule: add functionality to the material with the more complex existing function.

Electrical Performance Indices

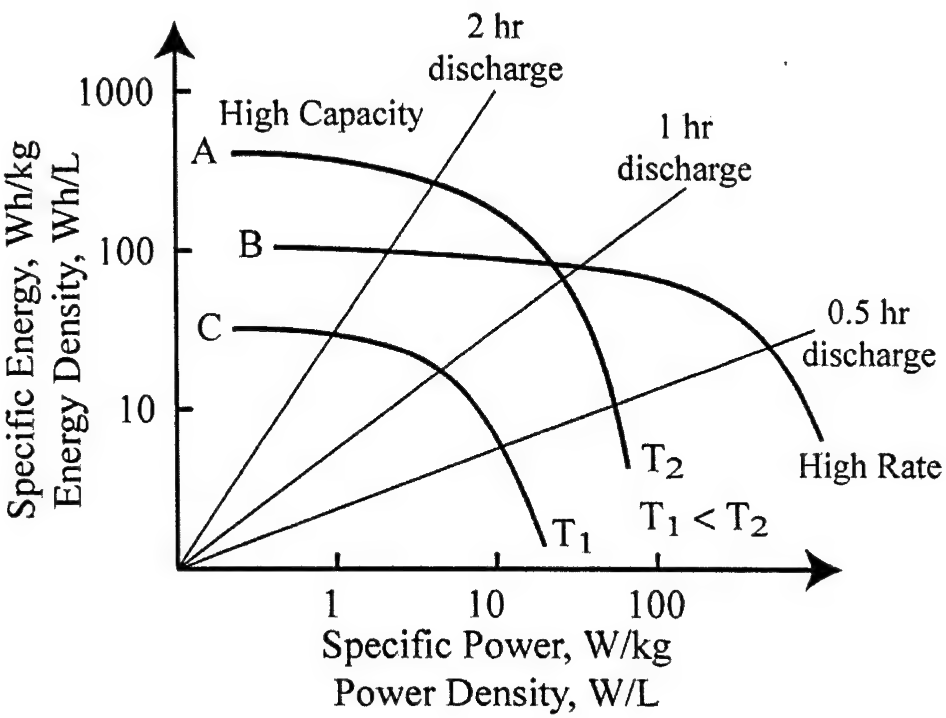
Ragone Plot for Electrical Energy Storage Devices



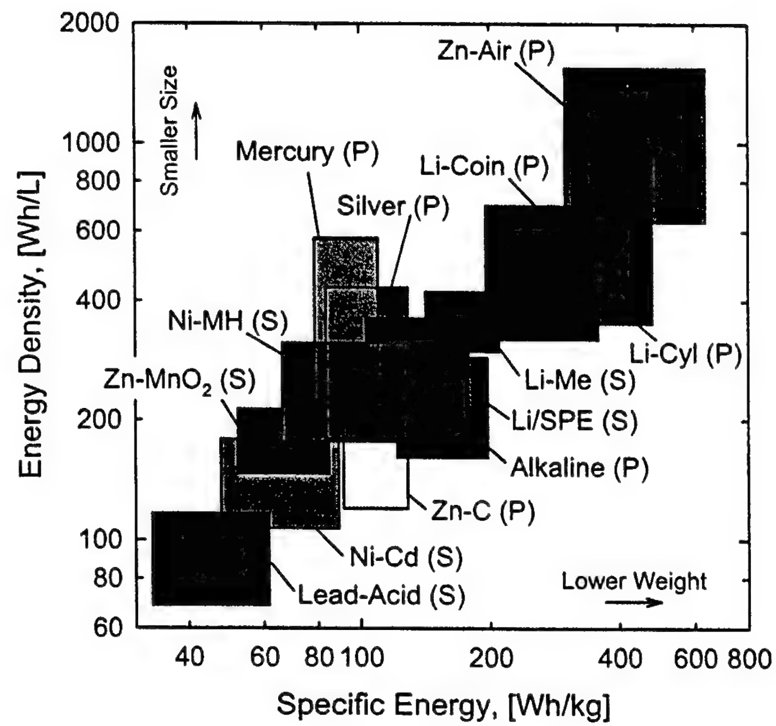
Wide range of Ragone performance due to intrinsic energy storage physics: **stretching** versus **breaking** of molecular bonds.

Electrical Performance Indices

Ragone Plot



Energy Density -vs- Specific Energy

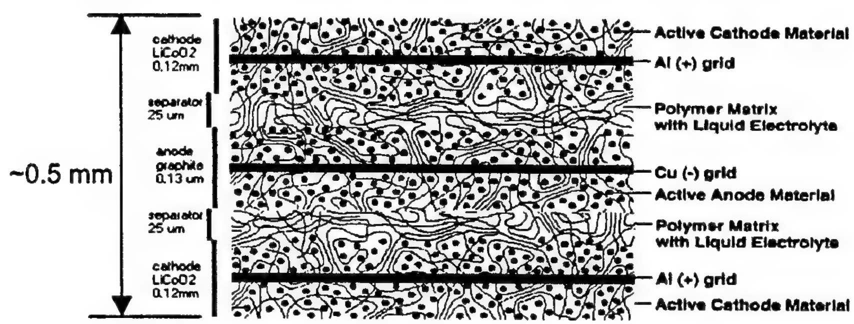


- **Li-Me (S)** and **Li/SPE (S)** cells show best rechargeable performance!!

Multifunctional Structure-PLI

Structure-PLI = Plastic Li-Ion Bicell(s) + Barrier-Layer Packaging + Structural Additives

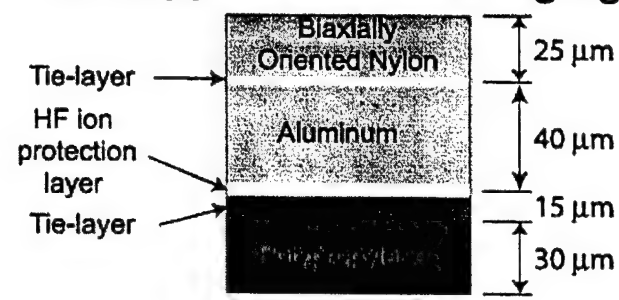
Telcordia's Plastic Lithium-Ion (PLI) Bicell



Nominal Properties

- 3.8 V & 7.2 mAh/cm^2
- $\rho = 0.14\ g/cm^2$
- E = 1020 MPa
- $\sigma_0 =$ 3.9 MPa

Dai-Nippon EL-40 Packaging

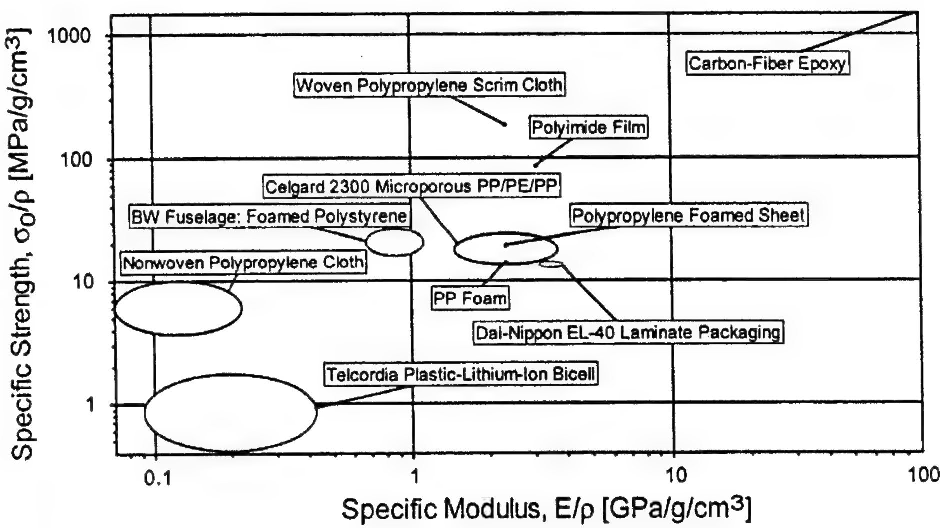


Nominal Properties

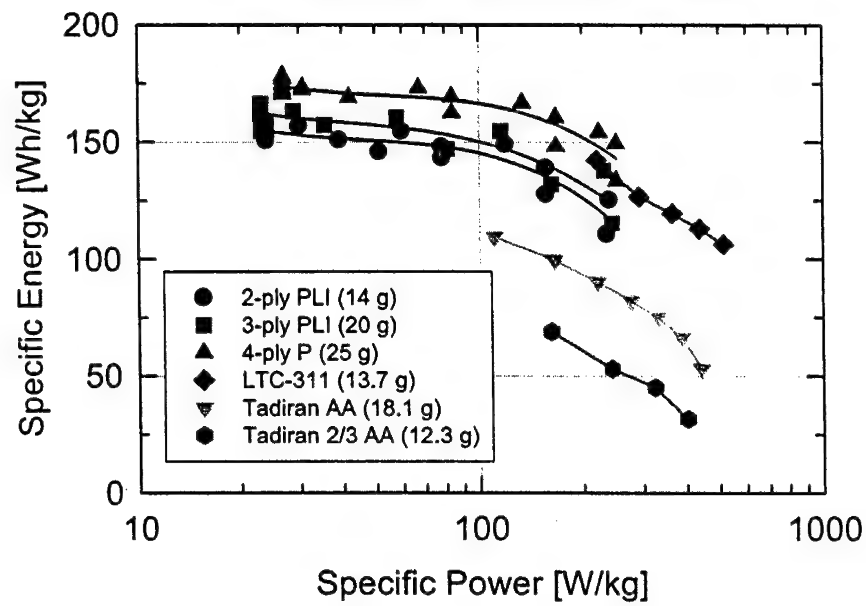
- E = 4400 MPa
- $\sigma_0 =$ 16.8 MPa

Structure-PLI Performance

Specific Strength –vs- Specific Modulus



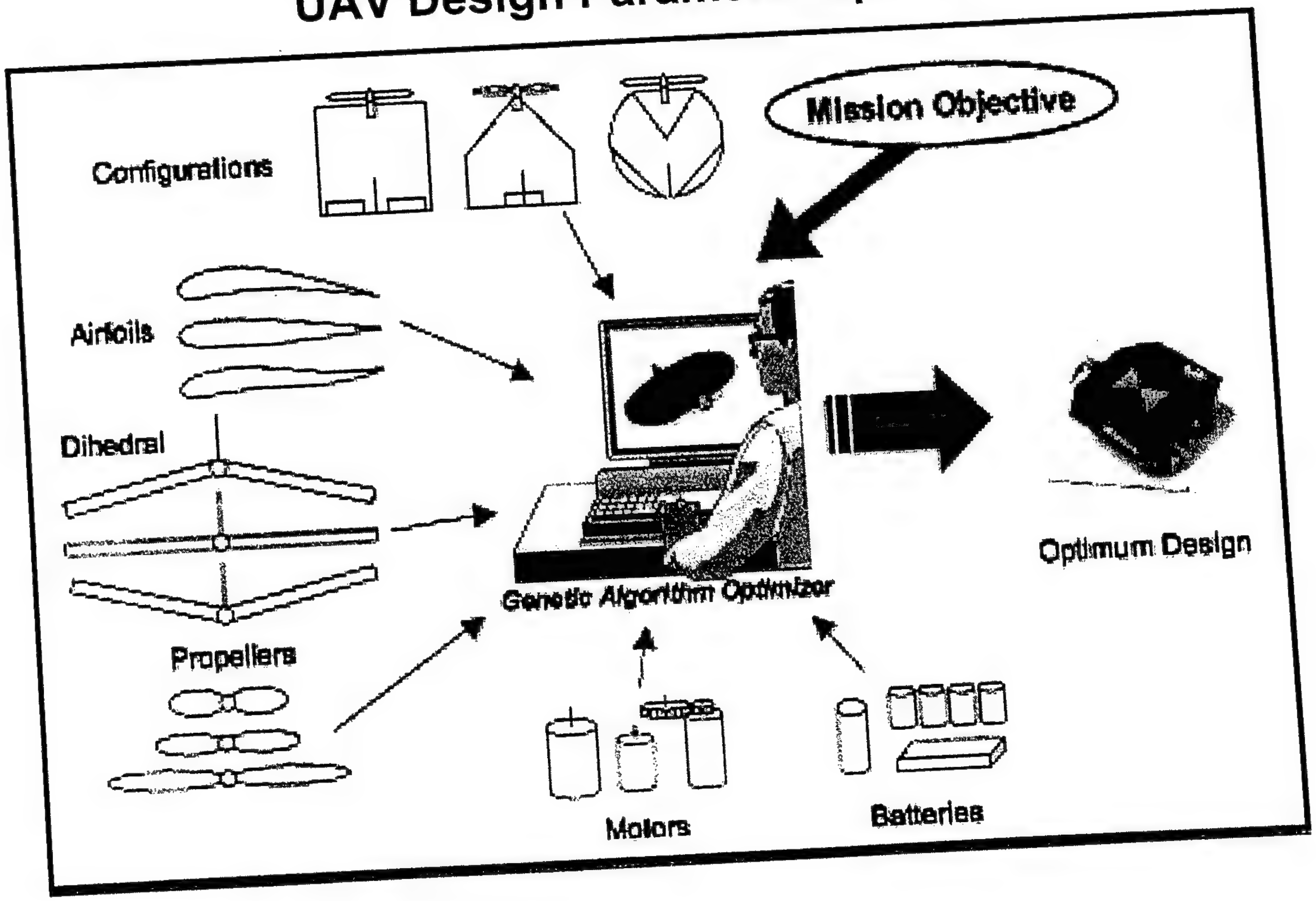
Ragone Data for Li Cells



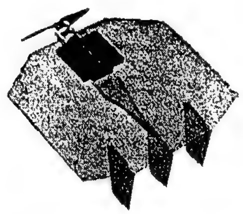
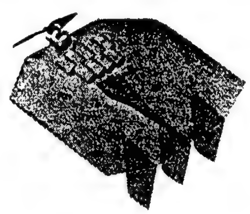
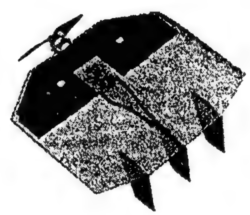
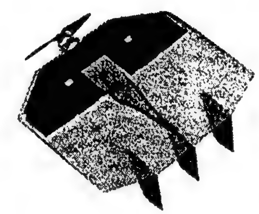
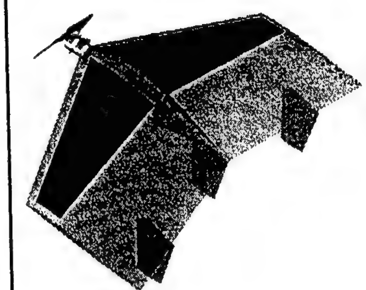
- Significant nonlinear, anisotropic behavior.
- Components with wide range of mechanical performance

Multidisciplinary Design Optimization of UAV's

UAV Design Parameter Space



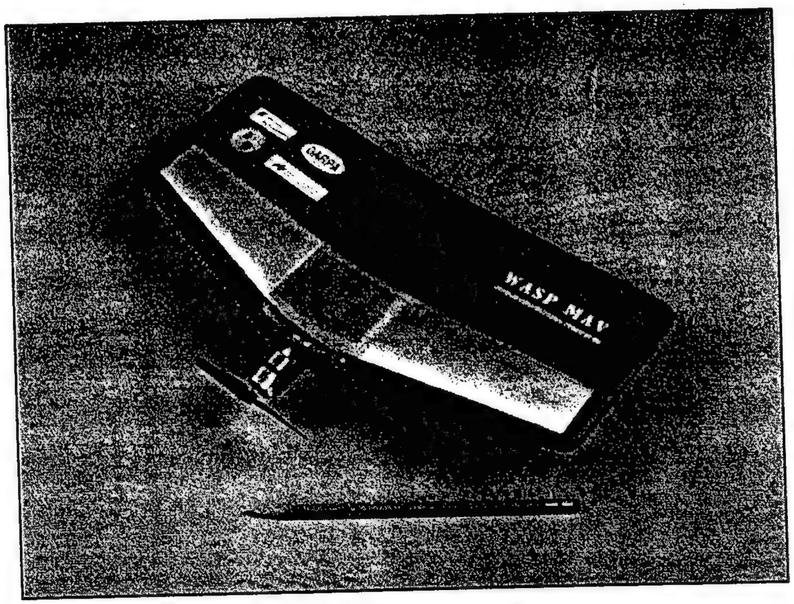
MDO Performance Analysis

Black Widow Design				Notional Design
1	2	3	4	5
 **Current Design**				
• Eagle-Picher cells • Primary • 15 cm span • 81 gram mass	• NiMH batteries • Rechargeable • 15 cm span • 71 gram mass	• 2-ply PLiON cells • Rechargeable • 15 cm span • 82 gram mass	• 3-ply PLI cells • Rechargeable • 15 cm span • 101 gram mass	• 4-ply PLI cells • Rechargeable • 28 cm span • 121 gram mass
• **30 min endurance**	• 5 min endurance	• 29 min endurance	• **34 min endurance**	• **70 min endurance!**
• Flight tested	• Flight tested	• Wind tunnel test • Structural mockup	• Wind tunnel test • Structural mockup	

WASP Multifunctional UAV

One hour and 47 minutes flight endurance time!

- 13 inch wingspan; 170 g total weight; 120 g structure-battery weight.
- Structure-PLI (silver) integrated into top and bottom of the wing.



- Aircraft detail design, fabrication, and test flying by **AeroVironment, Inc.**
- Structure-battery conceptual design and fabrication of the plastic-lithium-ion cells by **Telcordia Technologies**
- Structure-battery conceptual design and prototype development coordination by **Naval Research Laboratory**

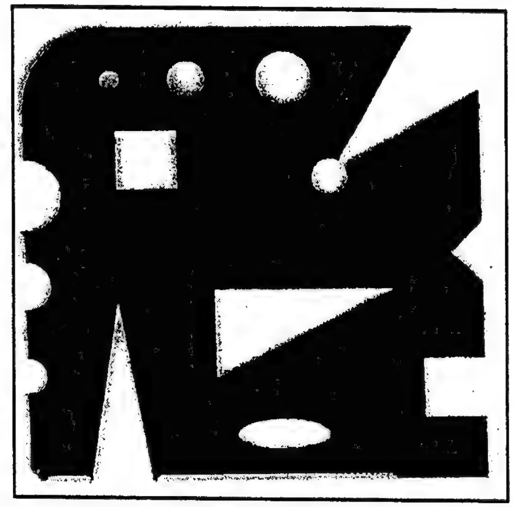
Benefits of multifunctionality clearly demonstrated by flight endurance of WASP UAV with fully integrated structure-battery!!!

Fabrication Procedures and Challenges

Fabrication Steps

- Cutting laminated PLI bicell to shape
- Pre-assembly and lead attachments
- Electrolyte imbibement
  - (<0.3% humidity)
- Lamina bonding and molding
- Packaging and sealing
- Electrical charging and testing

Cutting Test Geometry

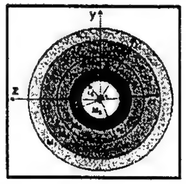


Automated Ultrasonic Blade Cutting

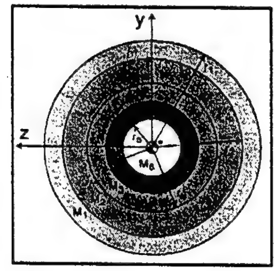
Include ~0.5 mm edge borders to avoid electrical shorting

Shape Factor: Size Does Not Matter!

2 x size



3 x size



Shape Factor is invariant WRT c-section size.

	Unifunctional	Multifunctional
Angle of twist:	$\theta_t = \dfrac{T\,L}{G\,K}$	$\theta_t^* = \dfrac{T\,L}{G_R K^*}$
Shape Factor for torsional deformation	$\phi_t^e := \dfrac{\theta_{circle}}{\theta} = \dfrac{2\pi K}{A^2}$	$\phi_t^{e*} := \dfrac{2\pi K^*}{A^{*2}} = 2\pi \left(\dfrac{E_R^2}{G_R}\right) \dfrac{\sum_{i=1}^{n} G_i K_i}{\left(\sum_{i=1}^{n} E_i A_i\right)^2}$

Multifunctional Composite Shape Factors generally depend on the **constituent material properties, shapes,** and **location** within the cross-section .

Health Management System Needs – Space Transportation Perspective

1st Air Force Workshop on

"Multifunctional Aerospace Materials"

October 23-24, 2002

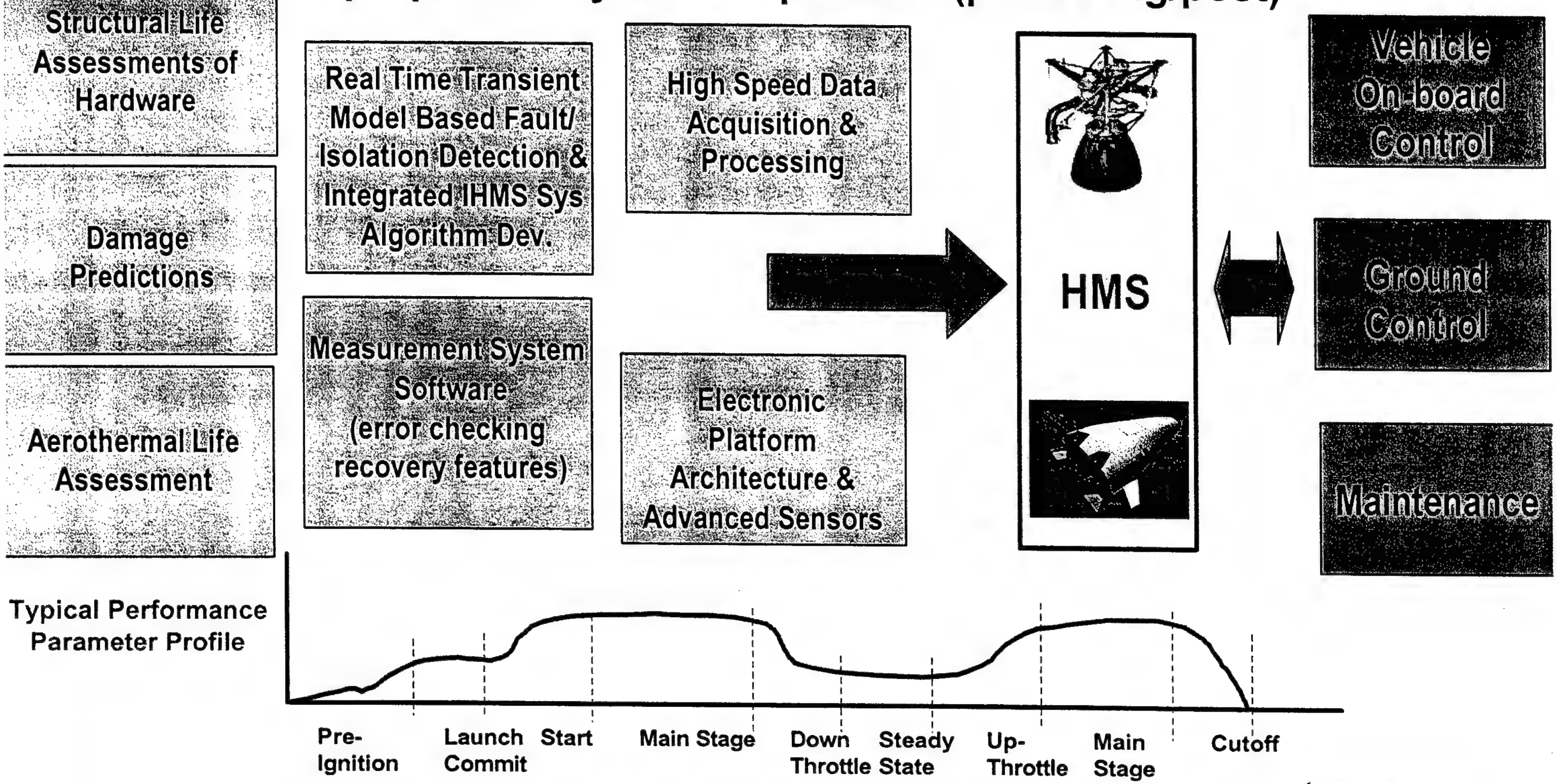
Purdue University

Munir M. Sindir, Ph.D.
Director
Advanced Analysis Processes
The Boeing Company
Rocketdyne Propulsion & Power Division
818 586-1627
munir.m.sindir@boeing.com

BOEING

Architecture of an Advanced Health Management System

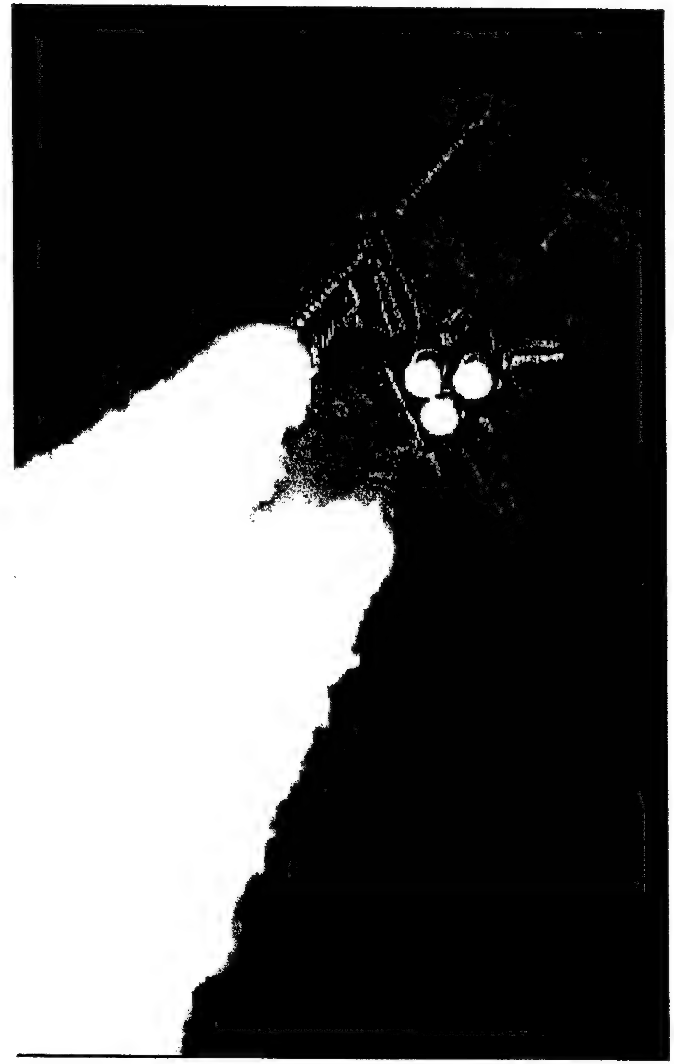
Real-time *"transient model"* based health management system capable of detecting and identifying the source of anomalies/wear during <u>all</u> phases of a propulsion system's operation (pre/during/post)



BOEING

Current Capabilities

- **Sensor Validation**
  - Reasonableness
  - Inter-channel / voting
  - Simple model
- **Detection / Isolation / Prognostics**
  - Dedicated sensors
  - Redlines
    - Flowpath
    - Vibration
- **Mitigation**
  - Channel switchover
  - Lock valves
  - Shutdown
- **Maintenance**
  - Schedule based on run time
  - Intrusive inspections



Future Capabilities

- **Sensor Validation**
  - System consistency / full non-linear model comparison
  - Frequency analysis
  - Sensor correlation
  - Sensor replacement / virtual sensing
  - Smart sensors
- **Detection / Isolation / Prognostics**
  - Non-linear model comparison
  - Artificial intelligence
  - Cameras
  - Plume spectroscopy
  - Trending
- **Mitigation**
  - Channel switchover
  - Adaptive control
  - De-rating
  - Adjust mixture ratio
  - Shutdown
- **Maintenance**
  - Vehicle-to-ground data telemetry
  - Maintenance for cause
  - Non-intrusive inspection
  - Direct damage measurement
  - Centralized maintenance center – fleet operations

BOEING

Current / Future Capabilities

	Sensor Qualification	Detection/ Isolation/ Prognostics	Mitigation	Maintenance

Current	• Reasonableness
	• Inter-channel / voting
	• Simple model
		• Dedicated sensors
		• Redlines
		  • Flowpath
		  • Vibration
			• Channel switchover
			• Lock valves
			• Shutdown
				• Schedule based on run time
				• Intrusive inspections

Future	• System consistency/full non-linear model comparison • Frequency analysis • Sensor correlation • Sensor replacement / virtual sensing • Smart sensors	• Non-linear model comparison • Artificial intelligence • Cameras • Plume spectroscopy • Trending	• Channel switchover • Adaptive control • De-rating • Adjust mixture ratio • Shutdown	• Direct damage measurement • Maintenance for cause • Non-intrusive inspection • Centralized maintenance center – fleet operations

Advanced Sensors

- **Functions**
  - High-frequency data measurements (e.g. pressure, vibration, stress)
  - Low-frequency data measurements (e.g. static pressure, temperature, mass flow, speed, displacement)
  - Plume spectroscopy measurements
- **Future characteristics**
  - Micro-sensors with built-in telemetry
  - Embedded sensors
  - Smart sensors

High Speed Data Acquisition And Processing

- **Functions**
  - Data collection
  - Sensor validation
  - Analysis algorithm
  - Event/anomaly detection
- **Future characteristics**
  - Multiple parallel processors
  - Fiber optics transmission
  - Real-time spectral analysis
  - Real-time expert system
    - Automated “smart” analysis

Real Time Transient Model Based Fault And Isolation Detection Algorithm

- **Functions**
  - Sensor output predictions based on actual engine operation
  - Fault predictions for anomalies
- **Future characteristics**
  - Real-time fault hypothesis testing and extrapolation
    - 1-D lumped parameter calculations
    - More sophisticated models
  - Multiple parallel processors

Measurement System Software

(Error checking, Recovery features)

- **Functions**
  - Sensors monitoring and qualification
  - Monitoring of output of real time transient model
  - Engine operation recommendations
  - Virtual sensing
- **Future characteristics**
  - Neural network/artificial intelligence/expert systems
  - Multiple parallel processors
  - Kalman filters
  - Adaptive control with HMS
  - Performance management
  - Diagnostics/prognostics

Aerothermo Life Assessments

- **Function**
  - Inputs:
    - Static pressure measurements
    - Temperature measurements
    - Mass flow measurements
  - Algorithms to predict effects of temperature and flow on hardware
- **Future characteristics**
  - Concurrent stochastic thermal modeling and validation
  - Smart thermal structure

Structural Life Assessment

- **Function**
  - Inputs
    - Vibration measurements
    - Stress measurements
    - Static pressure measurements
    - Temperature measurements
  - Algorithms to predict effects of vibration and stress on hardware
- **Future characteristics**
  - Probabilistic models to assess damage and structural integrity in real time
  - Numerical models to evaluate fault and fault propagation in real time

HMS Interfaces

- **Vehicle on-board control**
  - Recommendation for engine shut-down
  - Recommendation for engine throttle
  - Recommendation for fuel and oxidizer adjustments
  - Controller re-configuration
- **Ground control**
  - Recommendation for engine shut-down
  - Recommendation for engine throttle
  - Recommendation for fuel and oxidizer adjustment
- **Maintenance**
  - Hardware status
  - Recommendations for:
    - Hardware adjustments
    - Hardware overall
    - Hardware replacement
  - Engine history

Structural Health Monitoring of Aerospace Vehicles

Mark M. Derriso

AFRL/VASM

Structural Health Monitoring, Lead

Presented to

1st AIR FORCE WORKSHOP ON

"MULTIFUNCTIONAL AEROSPACE MATERIALS"

October 23-24, 2002, Purdue University,

W. Lafayette, IN

Overview

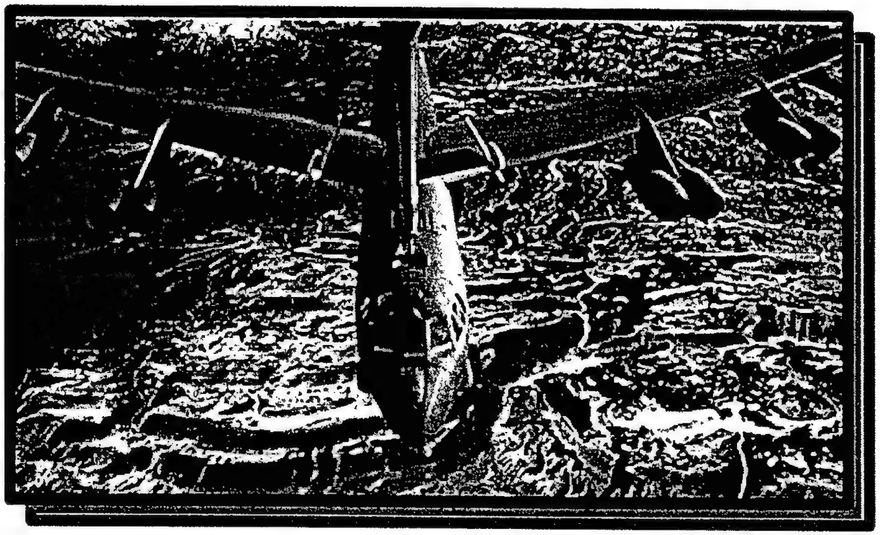
- Purpose
- Introduction
- Applications
- Technical Challenges
- Technical Approach
- Key Technologies
- Summary

Purpose

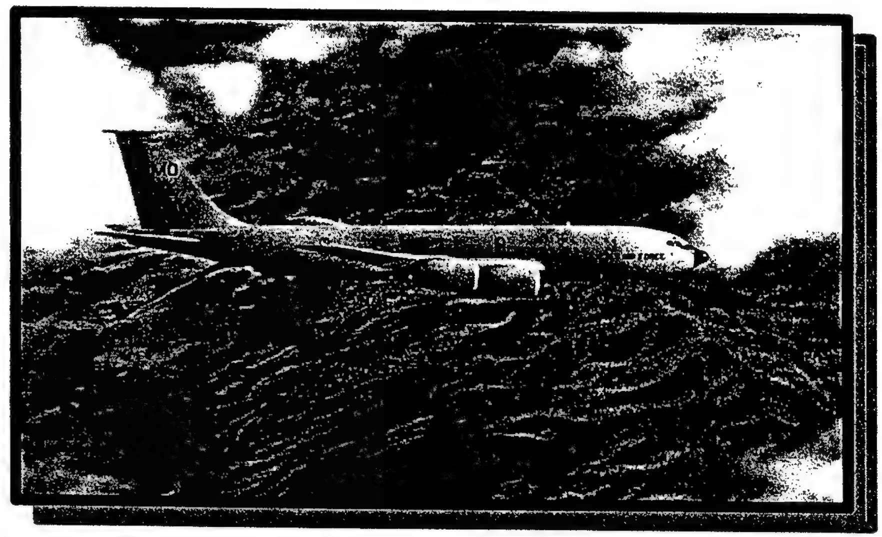
- To reduce the time and cost associated with scheduled inspections performed on structural components.
- **Benefits**
  - Reduce operation and support cost.
  - Reduce vehicle inspection times.
  - Maintain vehicle safety and availability.
- **Goals**
  - Reduce Air force O&M Cost.
  - Increase Operational Readiness.

Introduction

- It's a well-known fact that aircraft within the Department of Defense are aging rapidly.
- In many cases aircraft are operating well beyond their original design lives.



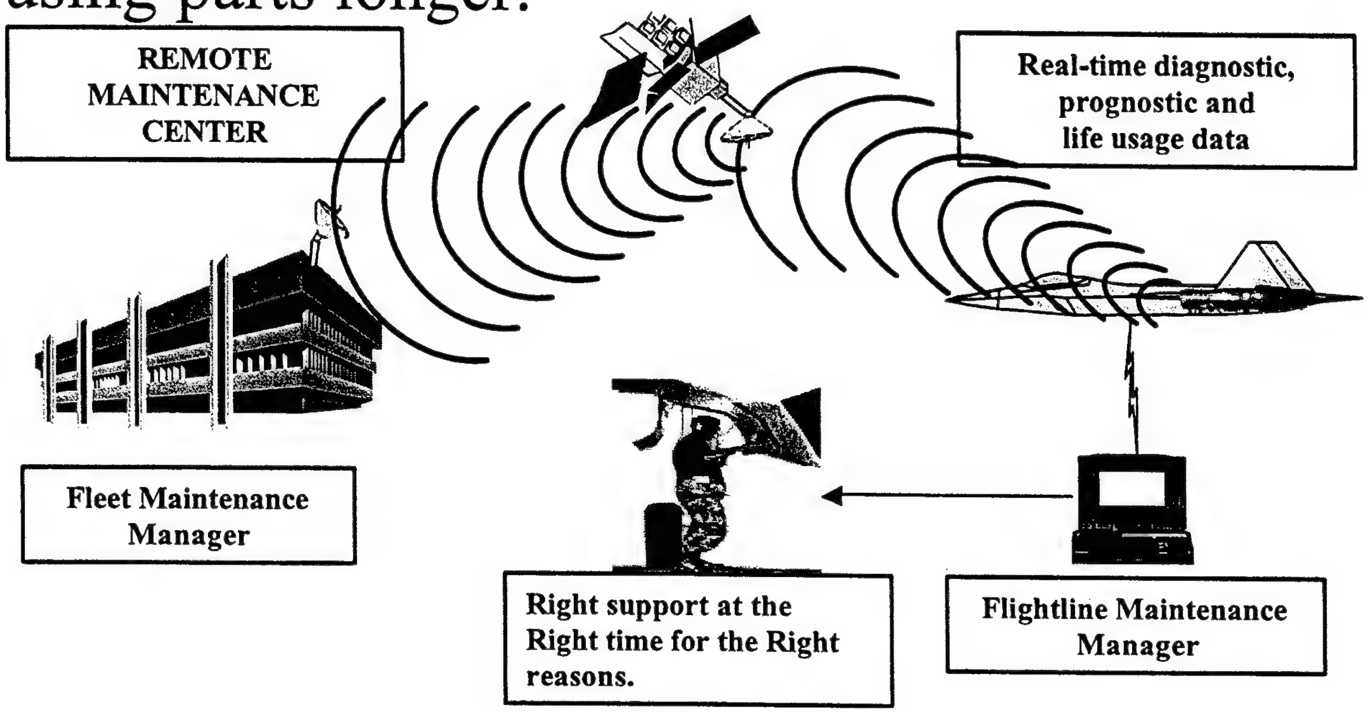
B-52



KC-135

Introduction

- In result, the Air Force emphasis has shifted from increasing performance to reducing the operational burden imposed by these older platforms.
- Decreasing the time required for maintenance and using parts longer.



Introduction

- "This study indicates that significant reduction in life cycle cost associated with maintaining and supporting structures could result in an operationally realistic return on investment. Specifically, if a 30% - 40% reduction in maintenance requirements is realized due to implementation and use of a health monitoring system."

  Health Monitoring System Technology Assessment- Cost Benefits Analysis.

  NASA/CR-2000-209848

  Renee M. Kent and Dennis A. Murphy

  ARINC,Inc., Annapolis, Maryland

Introduction

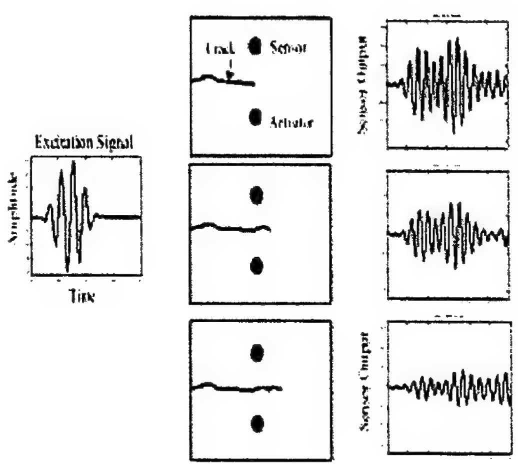
Four Levels of Structural Health Monitoring(SHM)

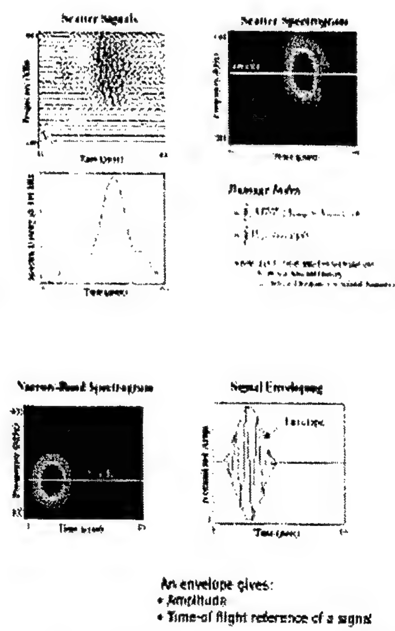
1. **Detect Damage**
   - Cracks, delaminations, corrosion
2. **Locate Damage**
   - Structural location of damage
3. **Quantify Damage**
   - Crack length, amount corroded, percent delaminated
4. **Predict Remaining Life**
   - How long before component fails

Introduction

Active SHM Technique (supervised)

Approach for Crack Monitoring





Damage Algorithm Development

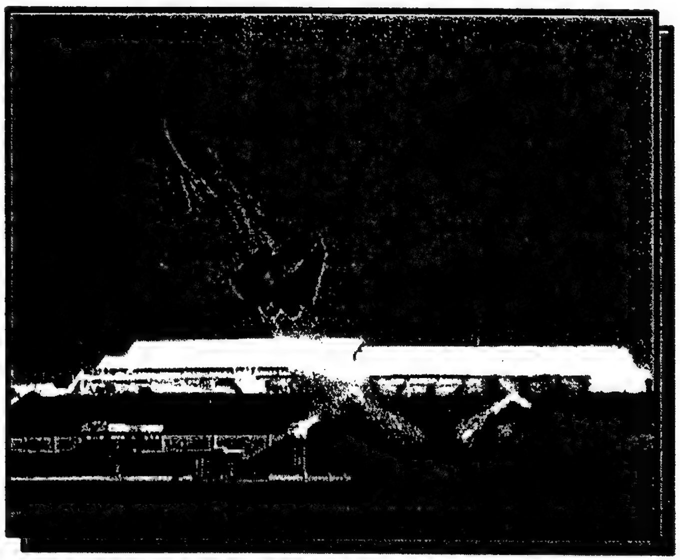
Forced Structural Excitation

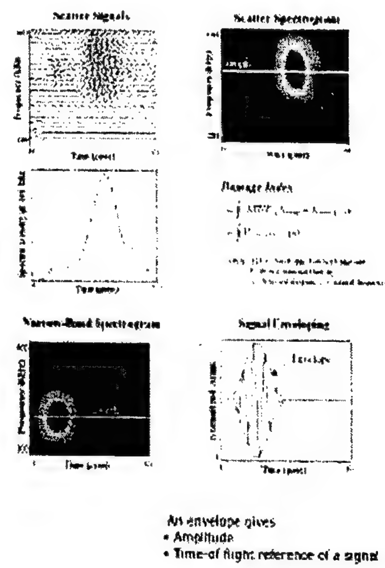
Signal Processing

Damage Algorithm

Introduction

Passive SHM Technique (unsupervised)





Damage Algorithm Development

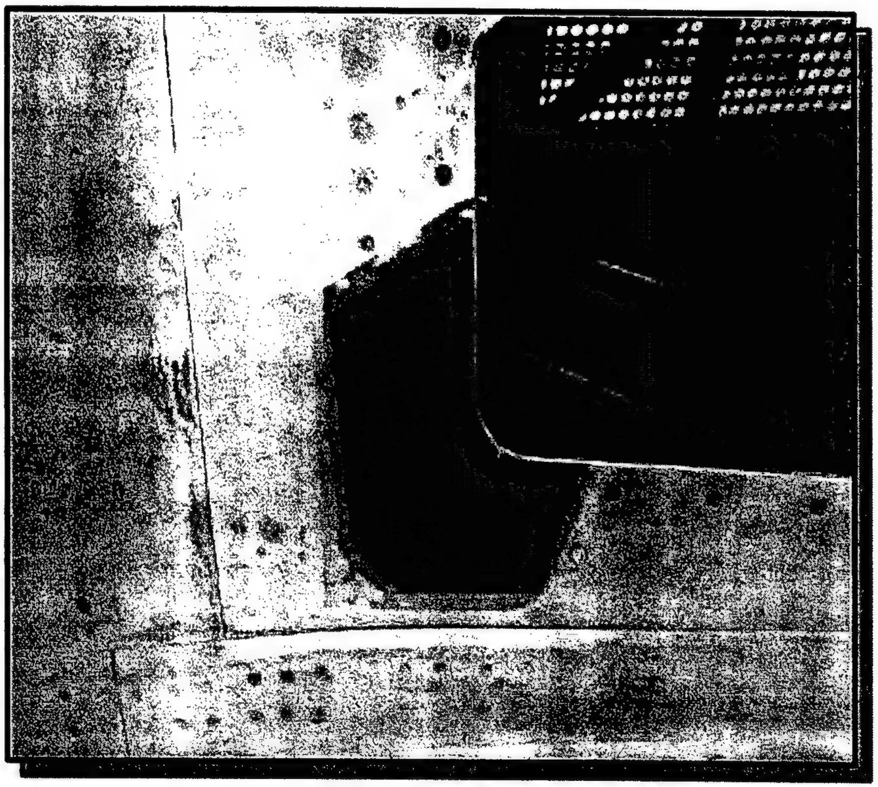
Operational Structural Excitation

Signal Processing

Damage Algorithm

Applications

Structural Health Monitoring of Bonded Repairs



- Bonded repair is one technique used to enhance the life of a damaged structure.
- Laboratory test have proven that a bonded repair could extend the life of a damaged structure by as much as a factor of eight.
- Bonded repair technology is currently being used on commercial and aircraft military aircraft.

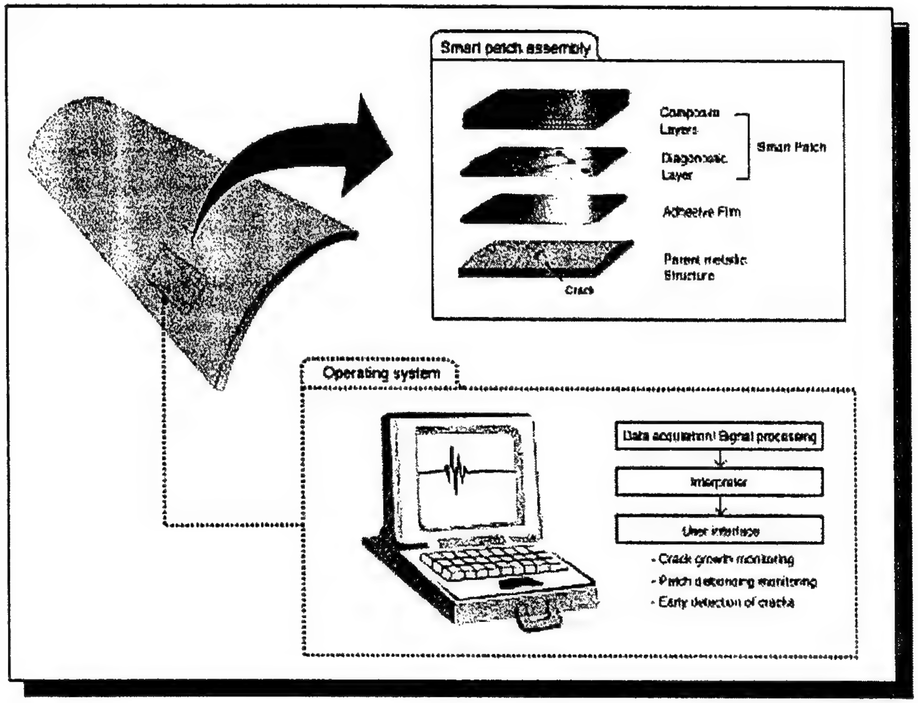
Applications

Structural Health Monitoring of Bonded Repairs

- However, the non-repaired inspection intervals of the damage under the patch is still performed because of the unknown condition of the bondline.
- By performing these non-repaired inspections, the Air Force is not receiving the full benefits of using the bonded repair technology.
- A possible solution to this problem is using a structural health monitoring system that would determine whether or not the integrity of the repair is decreasing.

Applications

Structural Health Monitoring of Bonded Repairs



Structural Health Monitoring System

Objective:

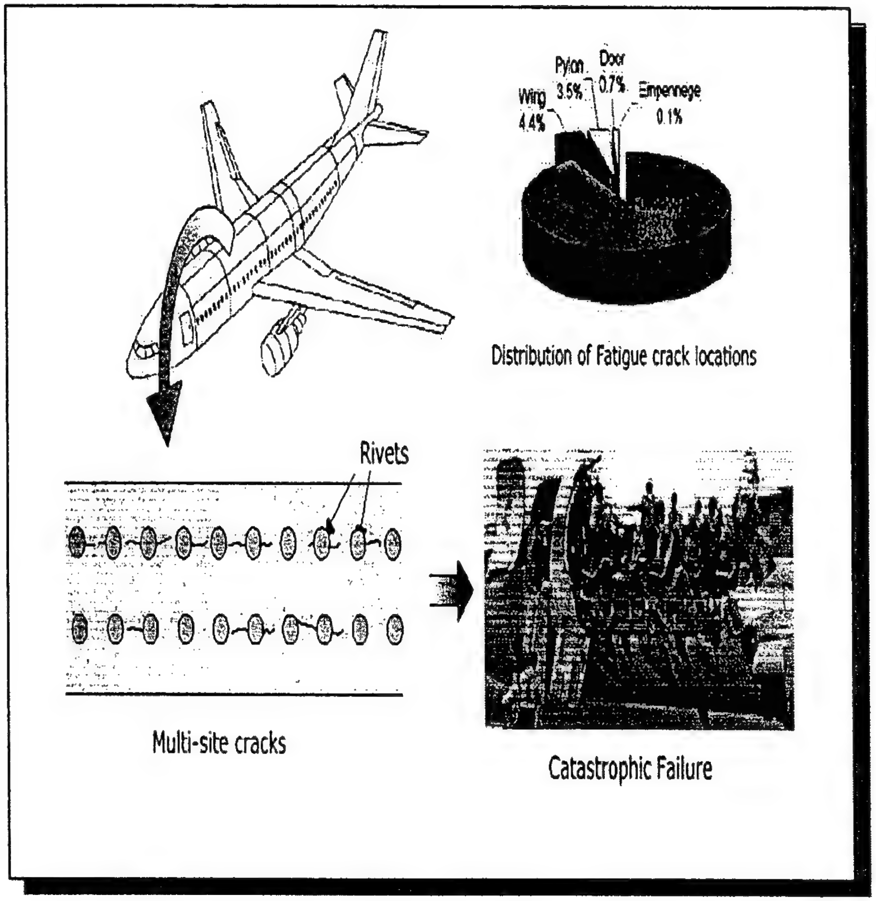
- Develop structural health monitoring techniques that will detect structural crack growth, disbonds and patch integrity of a composite bonded repair patch.

Payoffs:

- Enhance the life of a damaged aircraft structure.
- Maintain structural safety and availability.
- Reduce operational and service cost.

Applications

Structural "HOT Spots"Health Monitoring



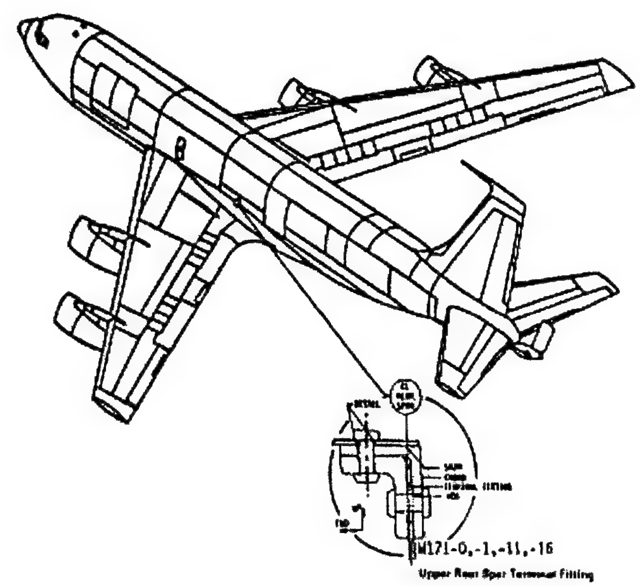
- Several aircraft in the Air Force fleet has known areas with structural problems.
- Maintainers have to inspect theses problem areas at predefined intervals.
- In some cases the problem resides in an inaccessible location such as the upper or lower wing spar which requires de-skinning the wing.
- Some of these inspections are quite costly.

Applications

Structural "HOT Spots" Health Monitoring

Objective:

- Develop structural health monitoring techniques that would detect and quantify structural cracks and corrosion in known problem areas on existing aircraft.

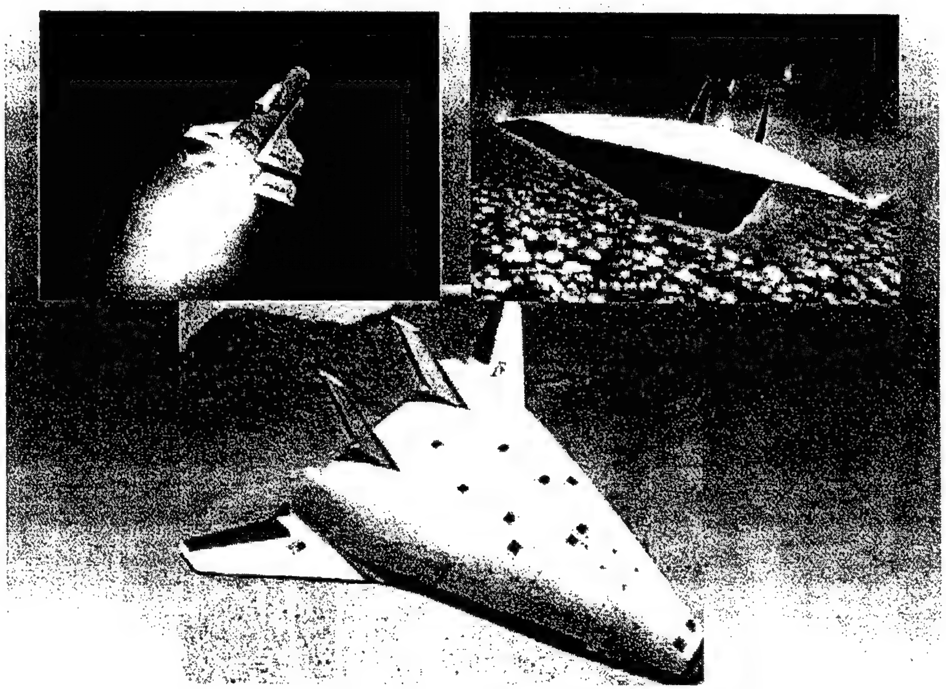


Payoffs:

- Reduce operation and support cost.
- Reduce vehicle inspection intervals.
- Maintain structural safety.

Applications

Space Operational Vehicle (SOV) Structural Health Monitoring

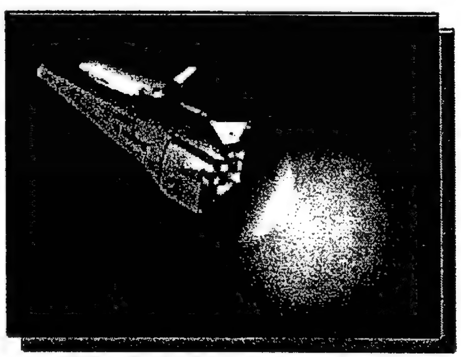


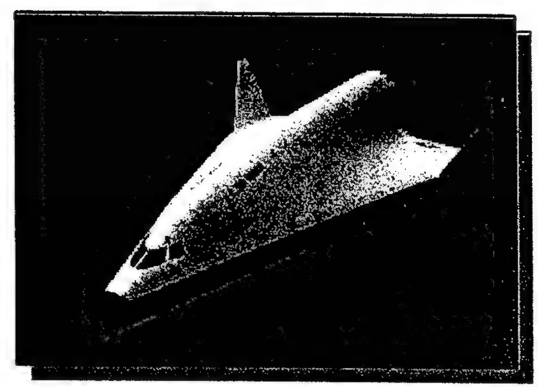
- The Space Operations Vehicle (SOV) is a key vehicle to meet future Air Force requirements in the areas of Control of Space and Global Engagement.
- The launch costs of the SOV must be one order of magnitude less than current state of the art in order to be successful.

Applications

SOV Structural Health Monitoring

- The key to reducing launch costs is reducing turn-around time.
- The System Requirements Document (SRD) for the SOV lists several requirements that have the purpose of reducing maintenance costs. In this presentation, we will concentrate on one of these objectives.
  - During normal conditions, the SOV shall have a turn-around time of 24 hours, with an objective of 12.
- To meet this goals, the assessment of the structure/TPS condition has to be reduce significantly.



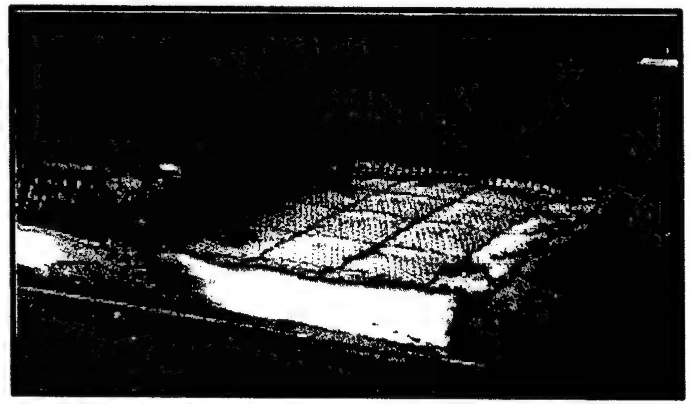


Applications

SOV Structural Health Monitoring

System Requirements

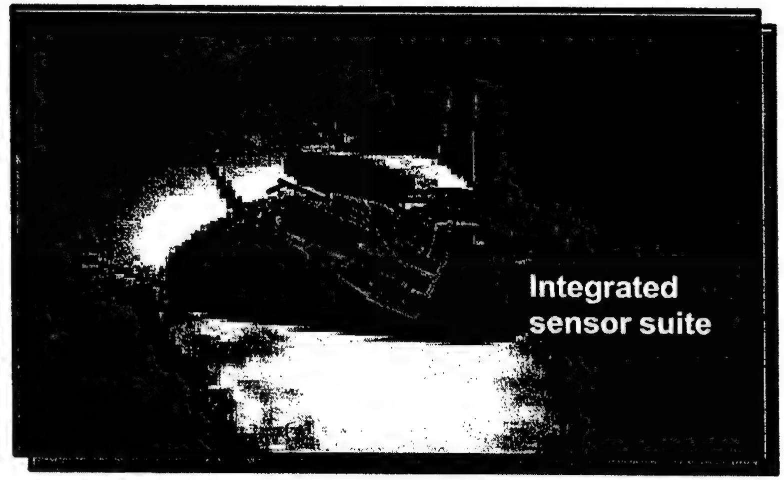
- An automated system that assess the health of the entire vehicles' structure/TPS within hours of completed mission and certify it for re-flight.
  - Acreage TPS
  - Leading edge TPS
  - Wing structure
  - Fuel tanks

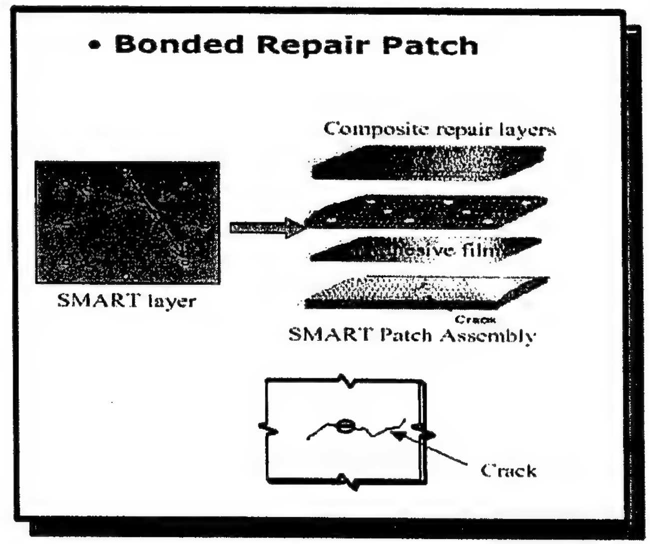


- SHM system needs to be able to do the following:
  - Detect damage in the structure/TPS
  - Locate damage
  - Diagnose damage (delamination, impact damage, mechanical attachments state etc.)
  - Prognosis of the health of the structure/TPS.

Technical Challenges

- **Sensors development**
  - high temperature (space)
  - wireless
  - reliable
- **Sensor optimization**
  - location
  - quantity
- **Data assimilation**
- **Data interpretation**
- **Structural life prediction methods**





Technical Approach

- Empirical Methods
  - Neural Networks
  - Pattern Recognition

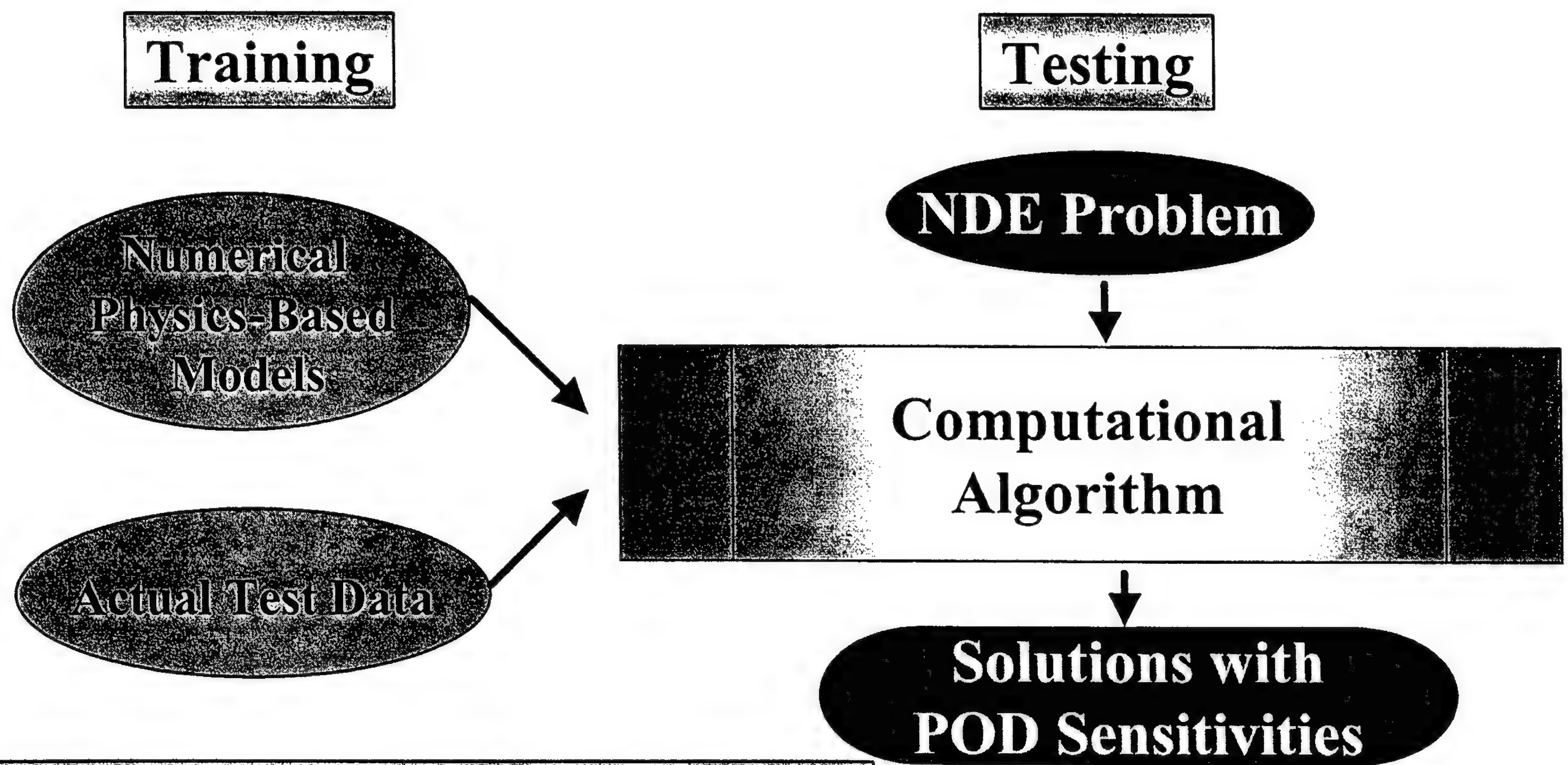
- Analytical Methods
  - Physics-based Modeling
  - Statistical Analysis

Hybrid Approach

Combine
Analytical and Empirical
Means for Optimum
Solution

Technical Approach

Pattern Recognition Approach

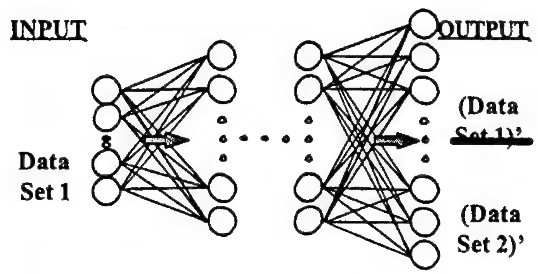


Basic Research:
- *Identify Material Property Features*
- *Discriminate Discontinuities*

Technical Approach

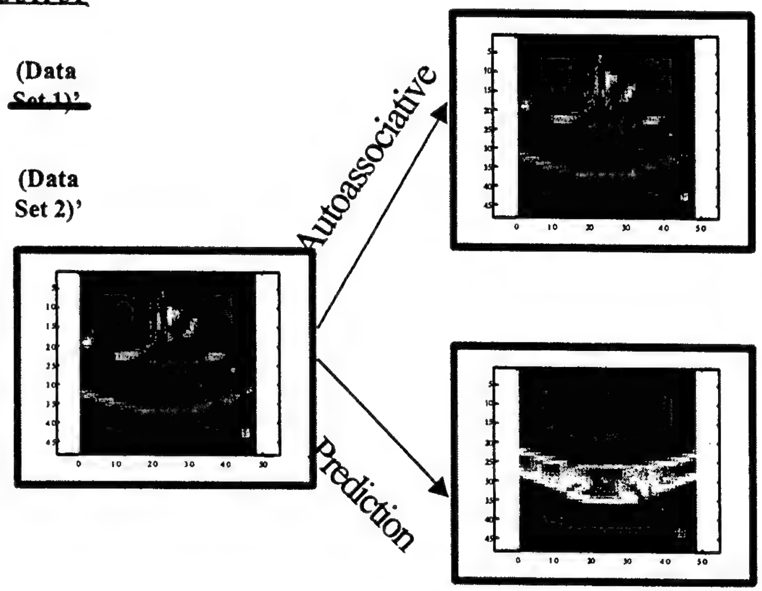
Data Fusion Approach

Autoassociative - Heteroassociative Neural Network (A-HNN)



Mathematical Transformation: Maps One Data Set to Two!

Patent Pending



***Basic Research*: Identify Common Invariant Features of "Relationship" Between Data Sets**

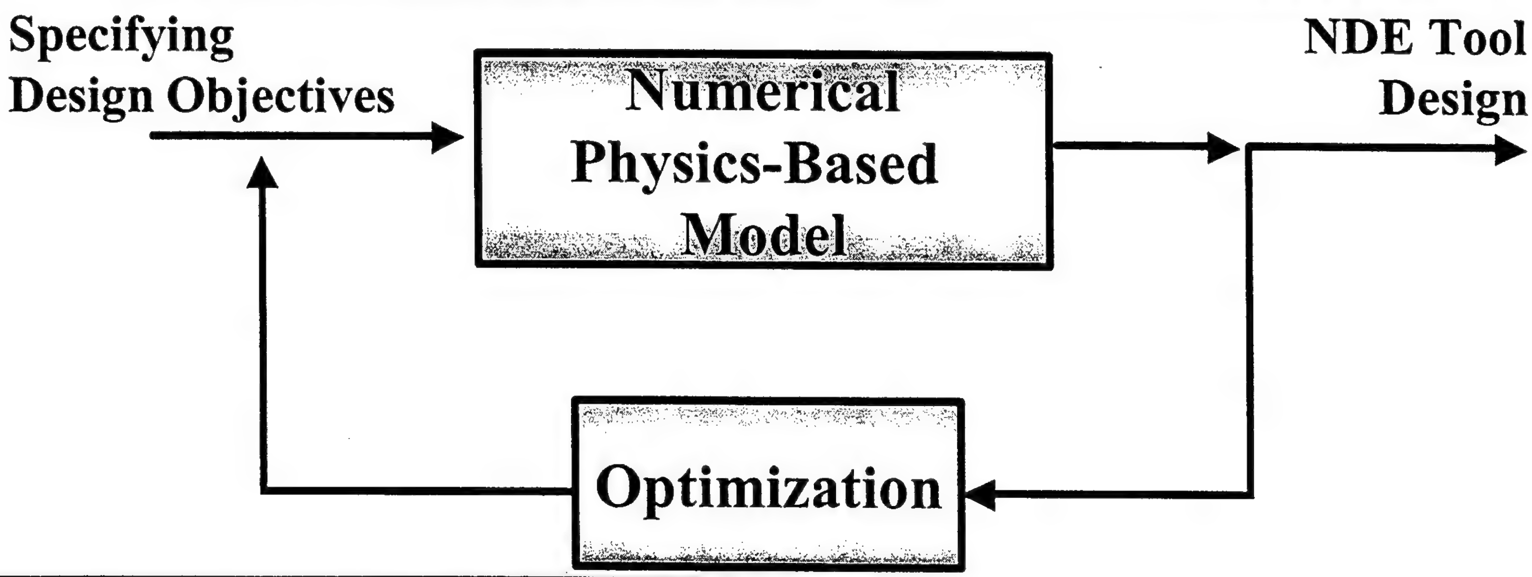
Technical Approach:

- Derive Transformation Matrix
- Establish Reliability Metric
- Experimental Validation

Technical Approach

Modeling Approach

Optimal Design of NDE Devices Using Ideal Concepts



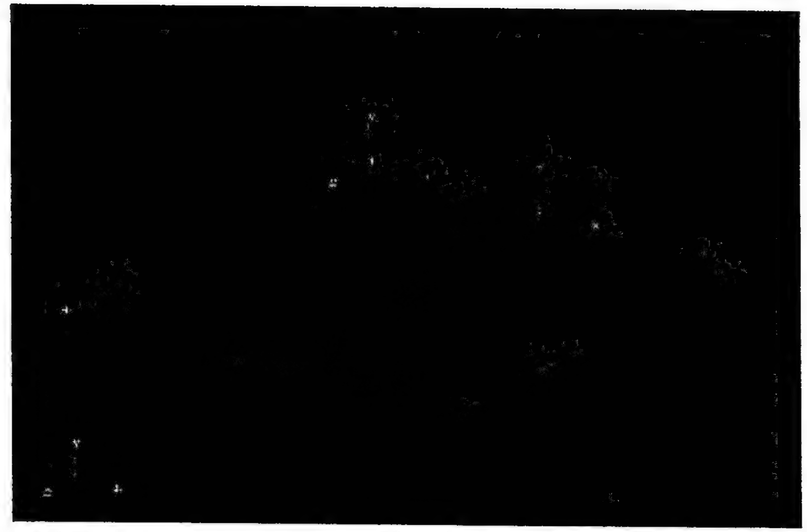
Basic Research:

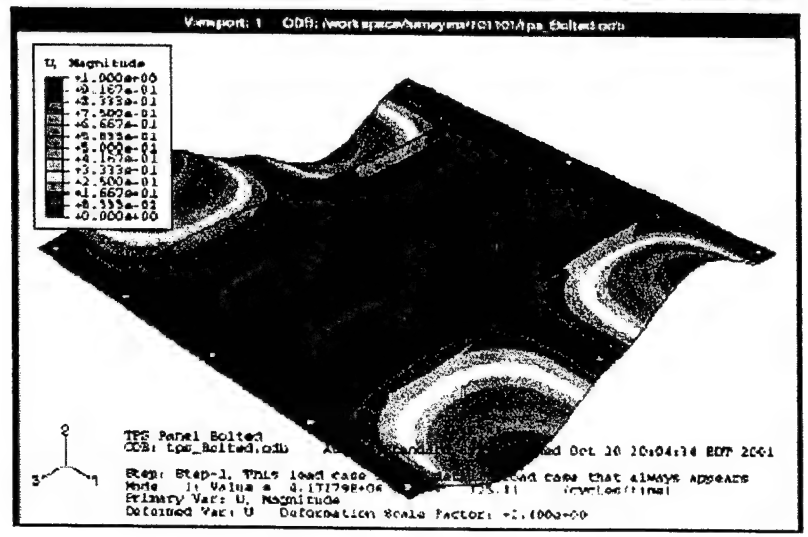
Identify Basic Design Principles

Identify Basic Design Axioms

Technical Approach

- Finite element modeling is done to determine the response of the panel.
- Advanced features are included such as the fasteners, contact, etc.
- Comparison is made with the experimentally observed response(s) to validate the model
- Sensitivities of the response(s) with respect to the damage states can be evaluated via analysis.

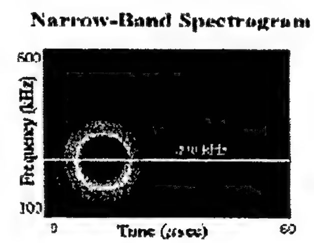


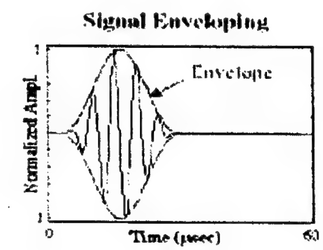


FEM of a TPS panel

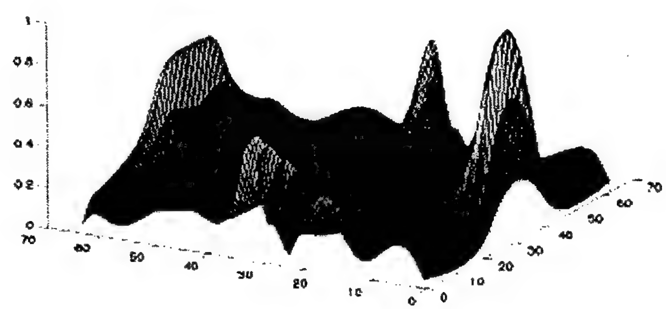
Key Technologies

- **Advanced Digital Signal Processing (DSP)**
  - Discrete Fourier Transforms (DFT)
  - Wavelet transforms
  - Digital filters
- **Advanced data analysis**
  - Feature extraction
  - Pattern recognition
  - Data fusion
- **Structural characterization**
  - Impact damage analysis
  - Structural fatigue analysis
  - Acoustics fatigue analysis



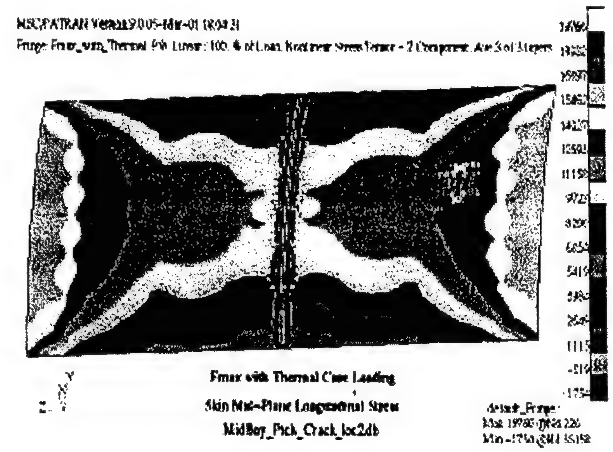


An envelope gives:
- Amplitude
- Time-of flight reference of a signal

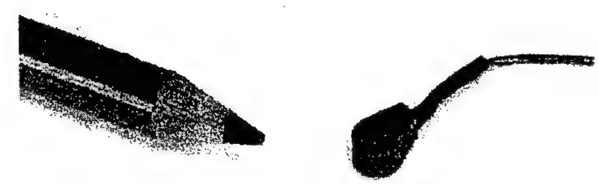


Key Technologies

- **Physics Based Models**
  - Structural Impact damage models
  - Structural Fatigue models
  - Life prediction models



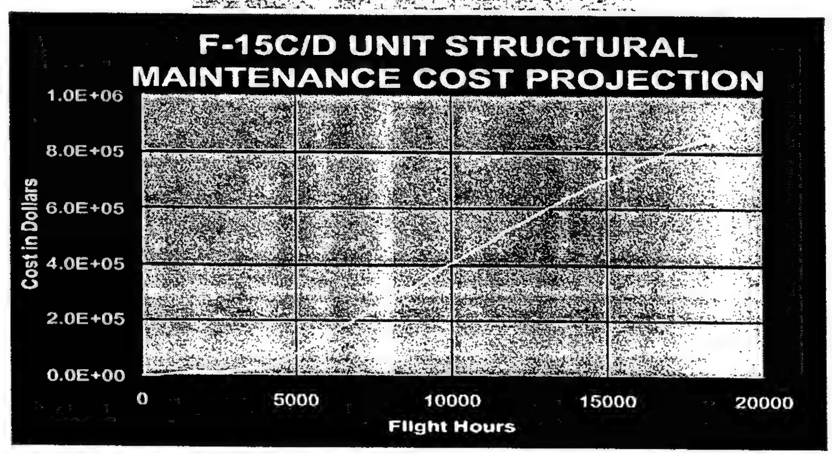
- **Data acquisition and instrumentation**
  - Sensor installation
  - Sensor integration
  - Sensor interrogation



Summary

- Warfighters have a need for this technology
- Reduction in O&M cost
- Maintain structural safety and availability

Technology Area	Technology Number	Technologies / Concepts	# Concepts technology is Enabling
Propulsion	PROP5	Affordable Prop Systems Technology	14
Com	COM3	Secure COMMs	13
[redacted]			



Materials That Sense Their Environment

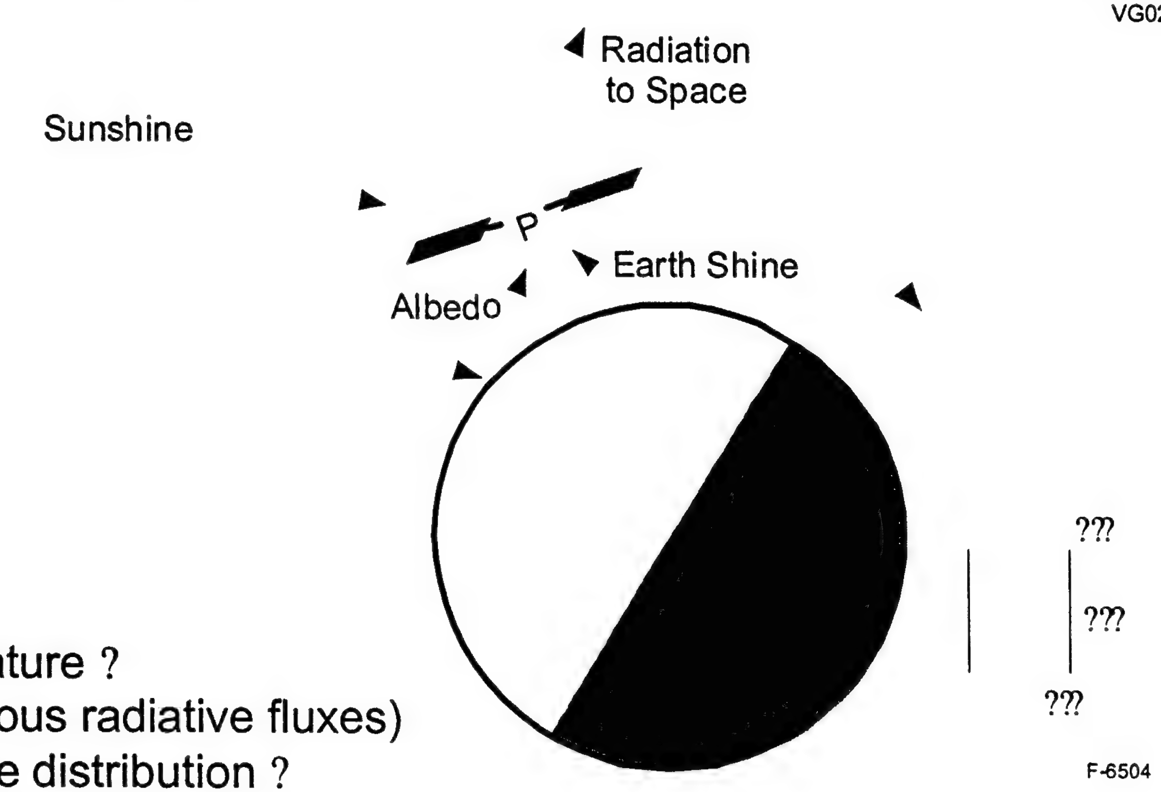
B. D. Green and P. B. Joshi
Physical Sciences Inc.
Andover, MA
green@psicorp.com

Presentation at:
Multifunctional Aerospace Materials Workshop

Purdue University
24 October 2002

Near-Earth Spacecraft Thermal Environment

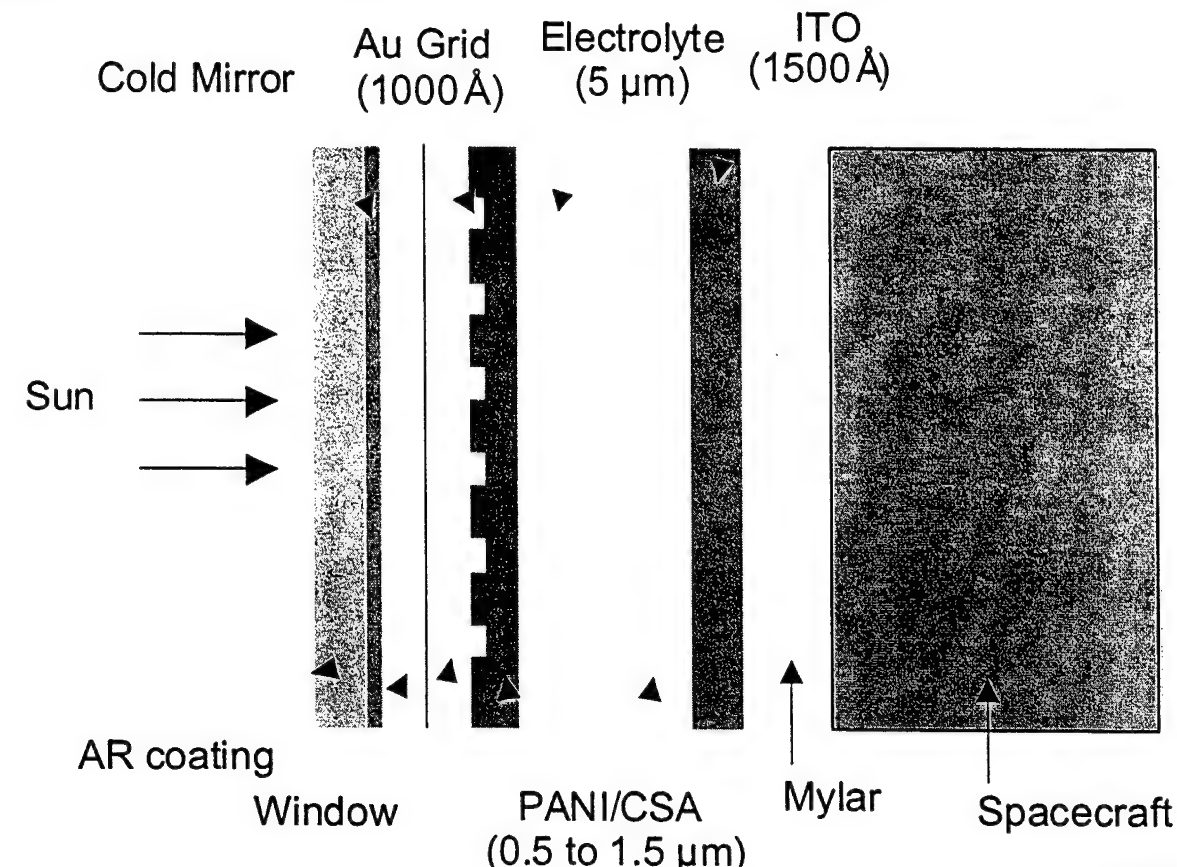
VG02-275-1



- ? Spacecraft temperature ?
  f(equilibrium of various radiative fluxes)
- ? Internal temperature distribution ?
  f(conduction within spacecraft structure)
- ? Temperature cycling as spacecraft moves in/out of eclipse
- ? Radiation to space, solar input, internal power must be controlled to maintain spacecraft systems (especially electronics) within operating temperature (-30 C to 65 C, typical)

Electrochromic Thermal Control Device Structure

VG02-275-2



F-4094b

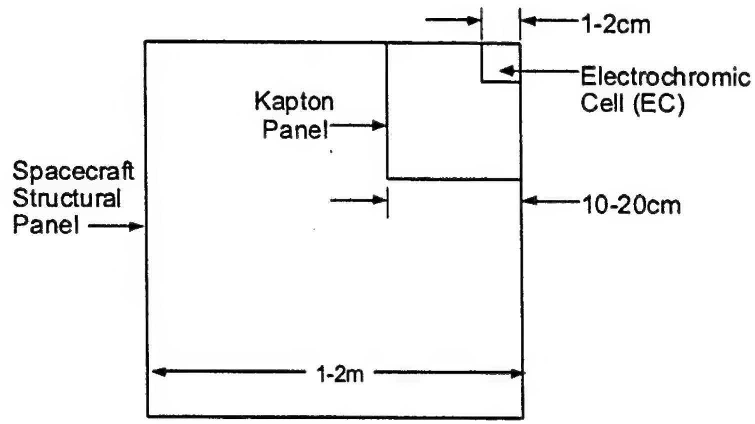
? Battery-like cell; charge changes optical properties

? The entire EC device is no more than 7 mils thick (0.177 mm) dominated by Mylar substrate (can be reduced to 0.9 mil)

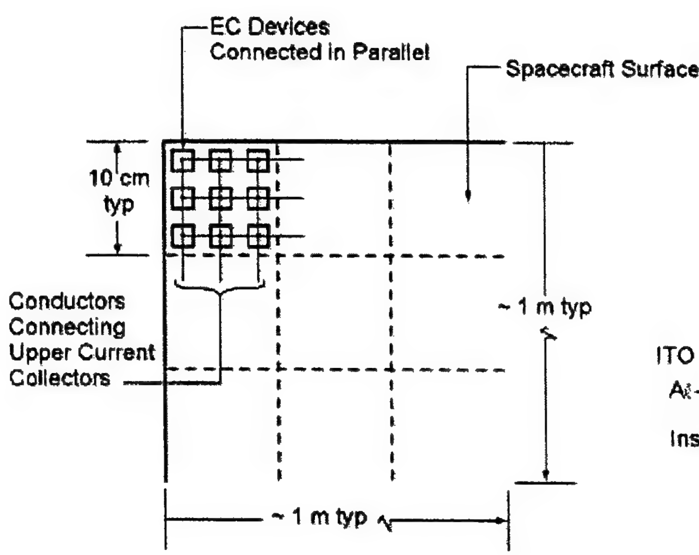
? Goal: thin-film flexible device thermostatically controlled

Concept for Integration of Electrochromic Devices into Spacecraft Structure

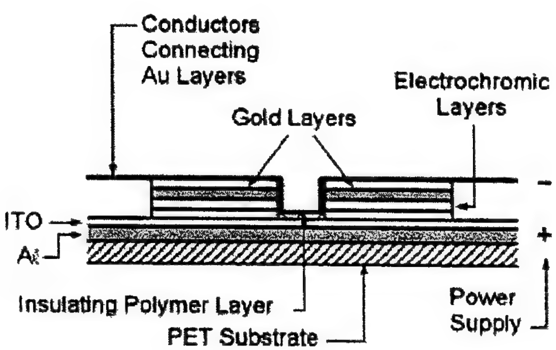
VG02-275-3



D-8280



(a)



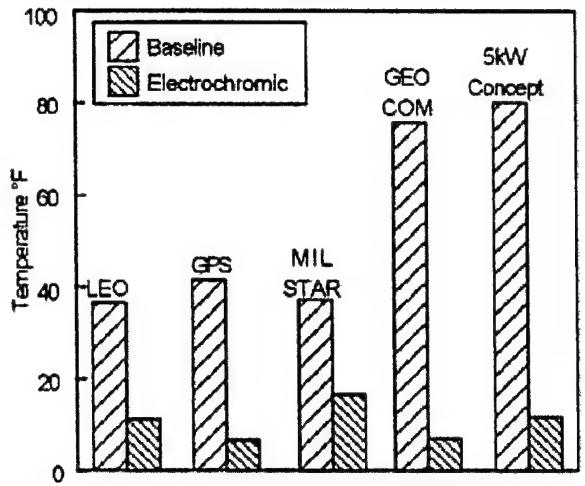
(b)

E-3022d

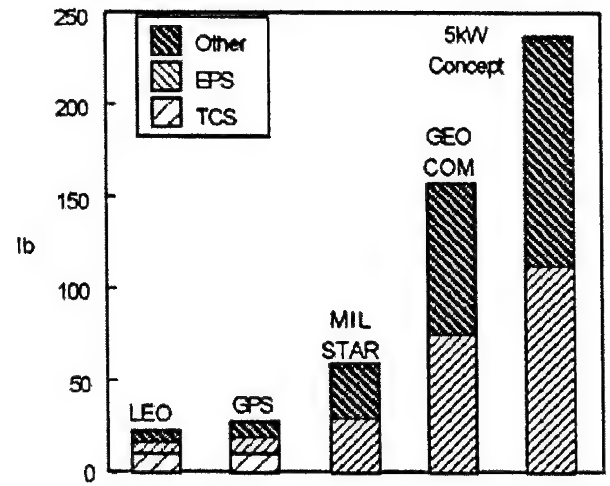
PSI

Benefits of Thermal Control with Electrochromics Technology

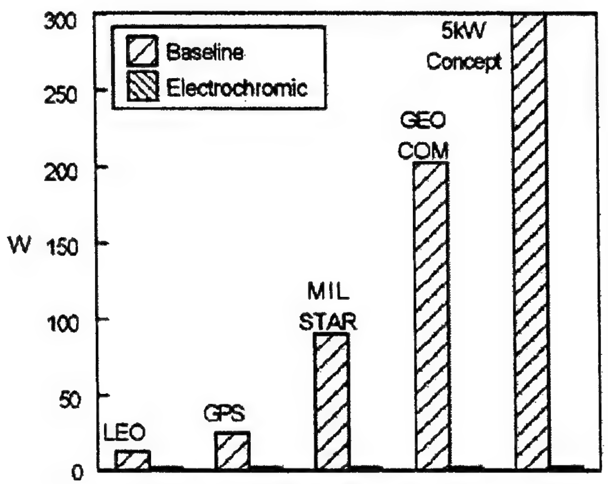
VG02-275-4



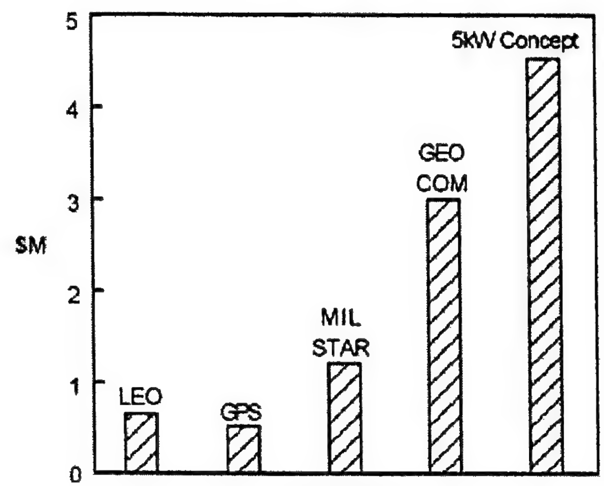
Component Temperature Variation
(a)



Weight Savings
(b)



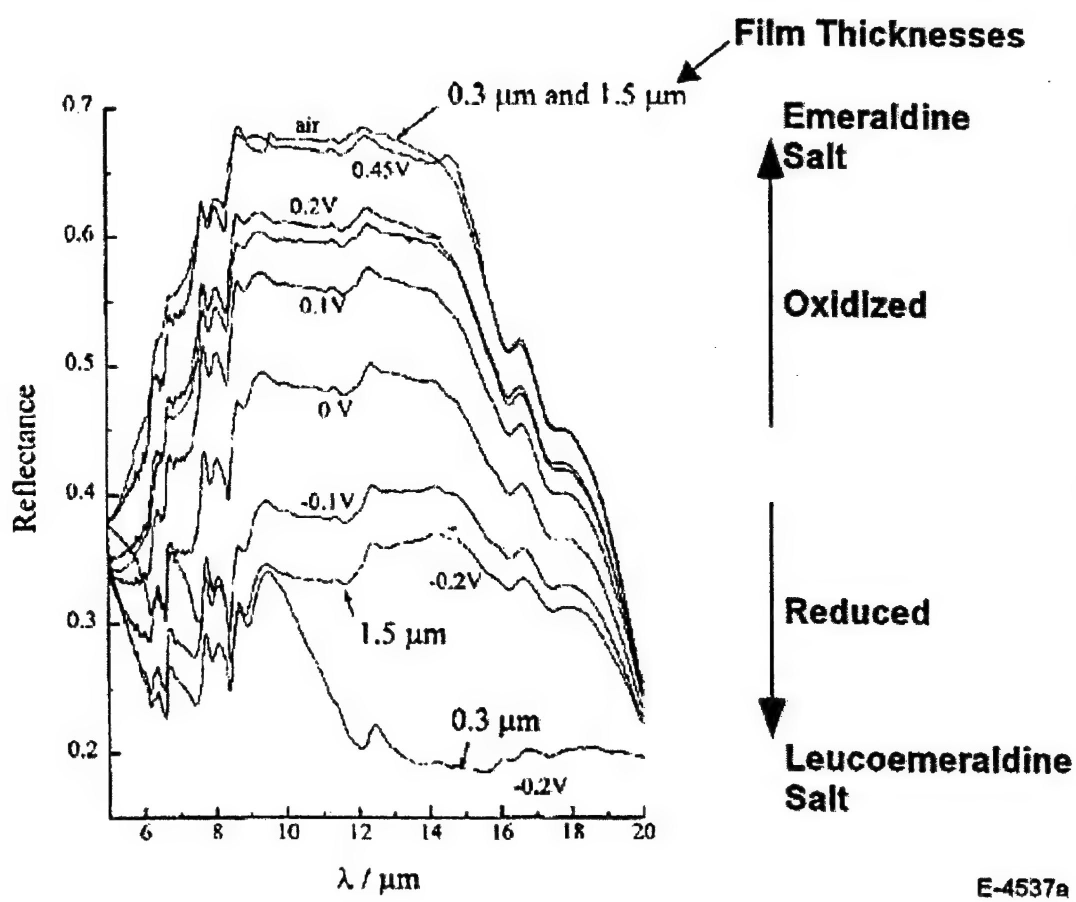
Heater Power
(c)



Cost Savings
(d)

Reflectance Variation with Film Oxidation

VG02-275-5



E-4537a

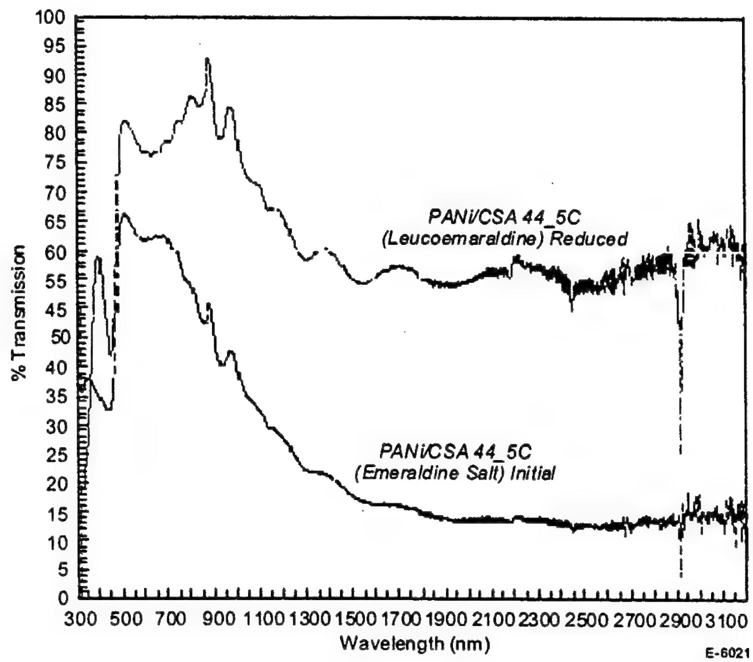
- PANI-CSA films 0.3 and 1.5 ?m, m-cresol solvent
- IR reflectivity variation between 0.7 and 0.2

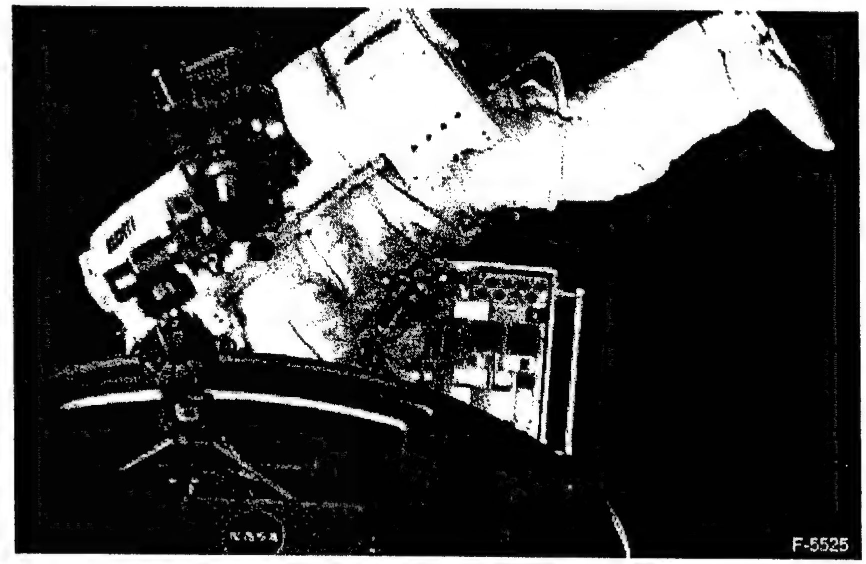
Reference: Topart and Hourguebie, *Thin Solid Films*, 352, p. 243, 1999.

Variable Emissivity/Reflectivity Materials First Flight Test

VG02-275-6

- ? Electrochromic materials for spacecraft thermal control, propulsion
- ? Vary R, a, ? in the visible IR by choice of substrate, active materials
- ? Alter optical properties via electro-chemical switching of polymeric materials





- ? Application to solar sails, s/c and subsystem thermal management
- ? Passive samples on MISSE carrier – first attached payload outside ISS (Aug 01)

PSI

Molecular Sensing Using Conductive Polymers

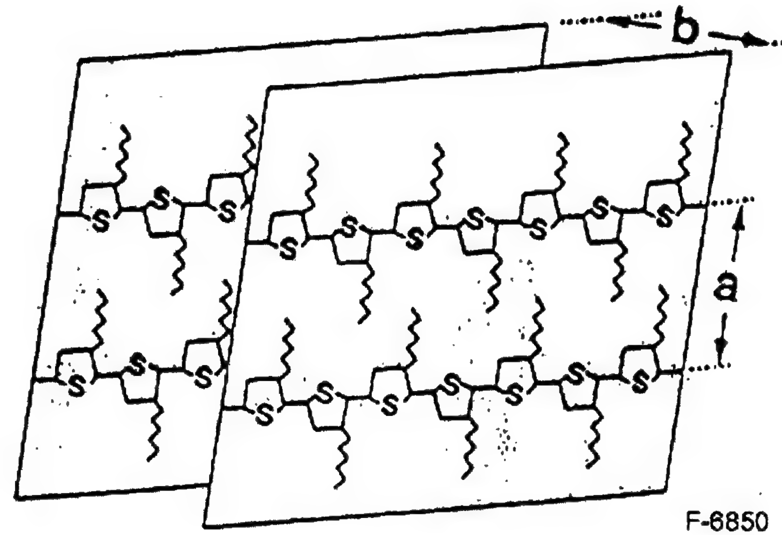
VG02-275-7

? **Inhibition of transduction**

- disrupt planarity of polymer backbone
  - swelling
  - chemical reaction with an additive
- dedoping
  - chemical reaction to remove dopant from polymer

? **Enhancement of transduction**

- target compound acts as a dopant to increase conductivity of the polymer
- interaction of target compound with sensing material increases planarity of polymer backbone



F-6850

Individual Chemical Alarm System (ICAS)

VG02-275-8

E-9183

? **Conductive polymer sensor system for**
- chemical warfare agents
- toxic industrial compounds

? **Real time detection**
- alerts wearer upon exposure
- stores exposure history

PSI

ICAS Prototype Badge Design

VG02-275-9

? **Simple user interface**
  - on/off switch
  - self-test feature
  - sampling interval selection
  - audible alert
  - tox class indication

? **Insertable sensor array chip**

? **AAA battery - 5-day lifetime**

? **Size**
  - 2.5 x 4.75 inches
  - 3.5 ounces

? **Downloads exposure data to Access database**

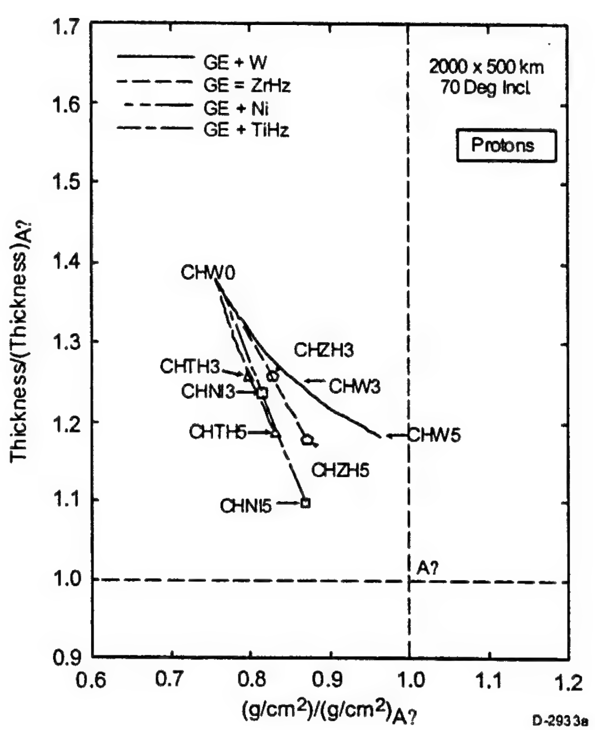
? **Exposure records**
  - exposure dose = concentration x time
  - logged every 30 minutes or + 20% dose increase

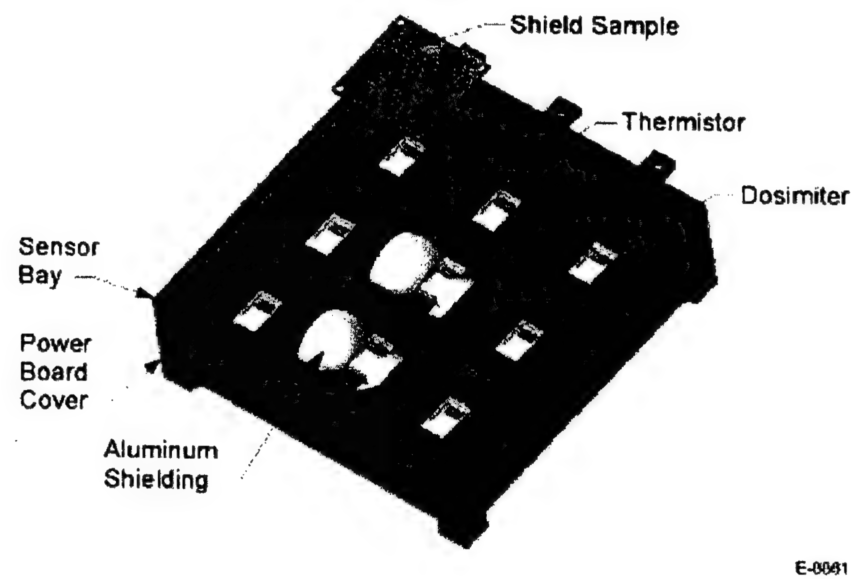
PSI

Advanced Radiation Shielding Materials SBIR

VG02-275-10

- ? Develop composites that provide more shielding per gram than Al
- ? Tailor composition to enhance *e* or *p* shielding for specific mission
- ? Benefit: significant mass savings reduce s/c weight or increase payload





- ? Commercial partner: Space Systems Loral
- ? Phase 3: Develop evaluation experiment
- ? Manifest: Geosynchronous telecom satellite: Brazilsat (2002 launch)
- ? Following activities: STRV1D, LMA panel

Summary

? **Conductive polymer compounds have been synthesized to maximize**
  - optical properties changes
  - response to toxic compounds

? **Sensors for control network**

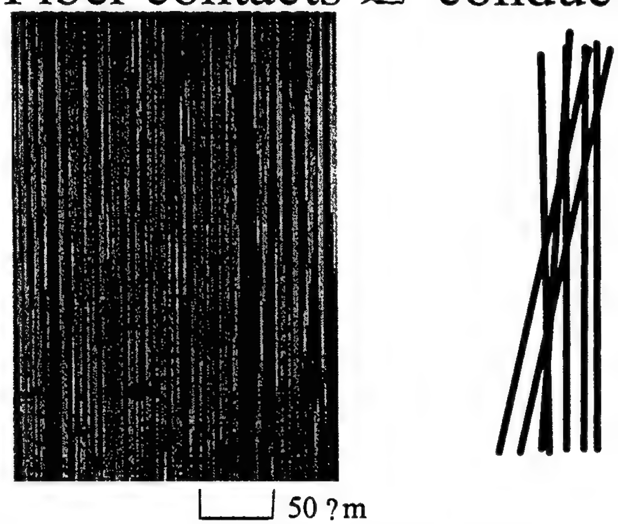
? **Undergoing demonstrations under real world conditions**

? **Polymer compounds are a useful accessory to composite structures**

Self-Diagnosis of Damage in CFRP by Electrical Resistance

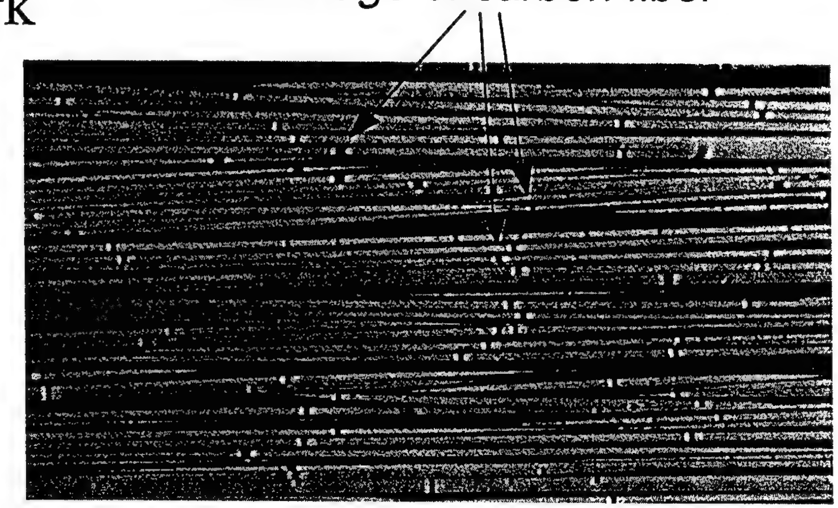
W. A. Curtin, Brown University,   N. Takeda, T. Okabe, J. B. Park, U. Tokyo

- Carbon fibers: electrically conducting
- Fiber contacts ✍ conducting network



Contacts Between Fibers
Due to Misalignment

breakage of carbon fiber



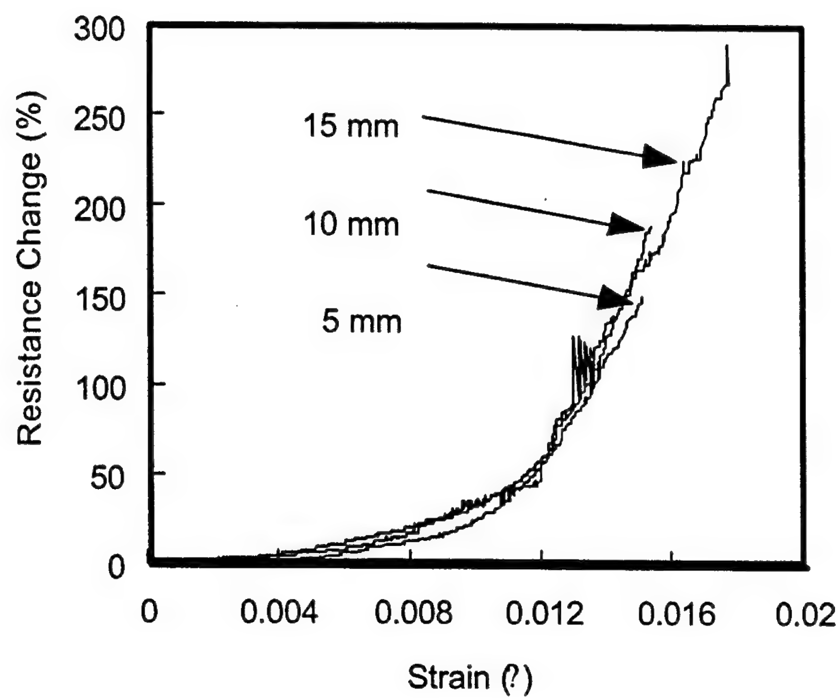
Fiber breaks (mechanical damage)
✍ electrical "damage"

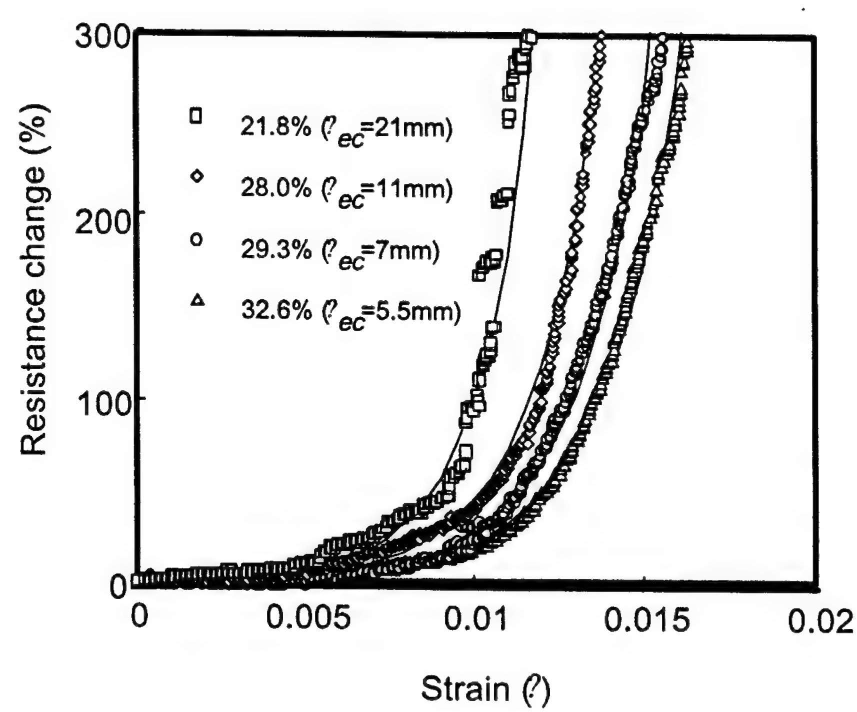
Electrical resistance monitors damage evolution

On-Board Damage Detection, Failure Prediction from Resistance

Large changes in resistance at small strains

Highly non-linear response with strain;
Can tune to coincide with failure strain



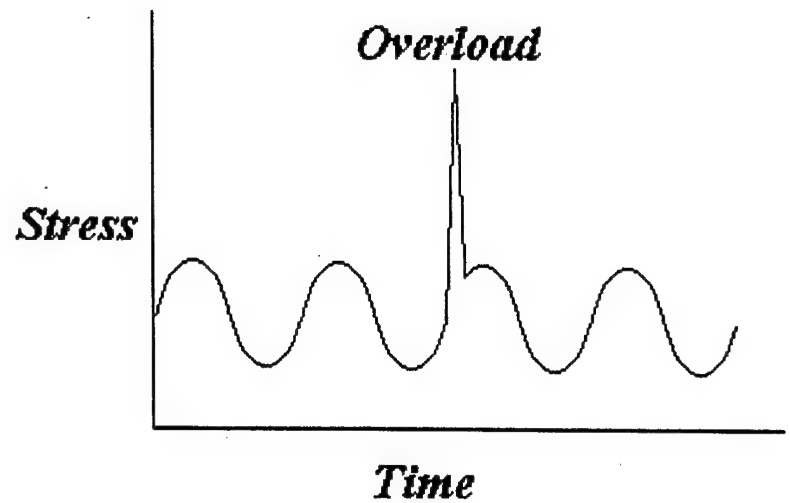


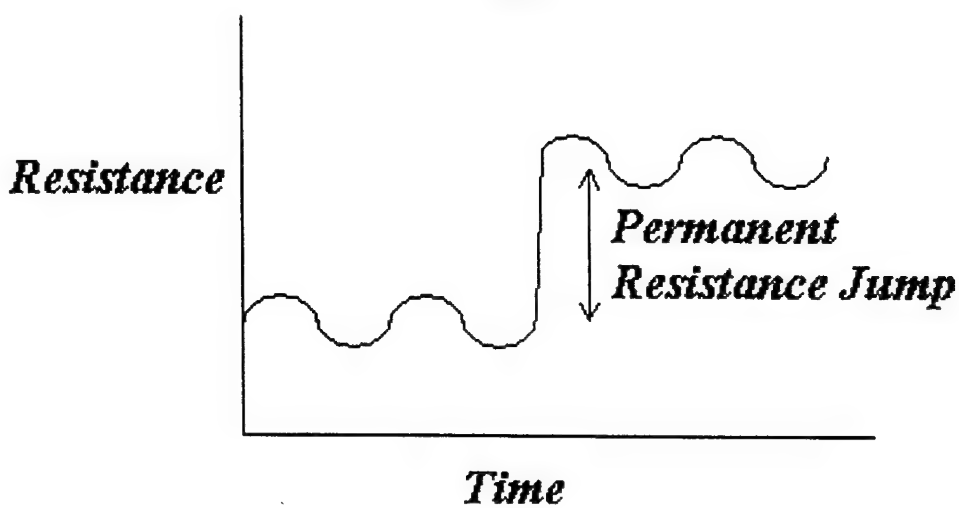
Resistance response can be tuned using fiber volume fraction

Resistance is independent of sample gauge length (spatial sensitivity)

Resistance carries a permanent record of prior damage

Critical for damage due to overloads





Some Issues:

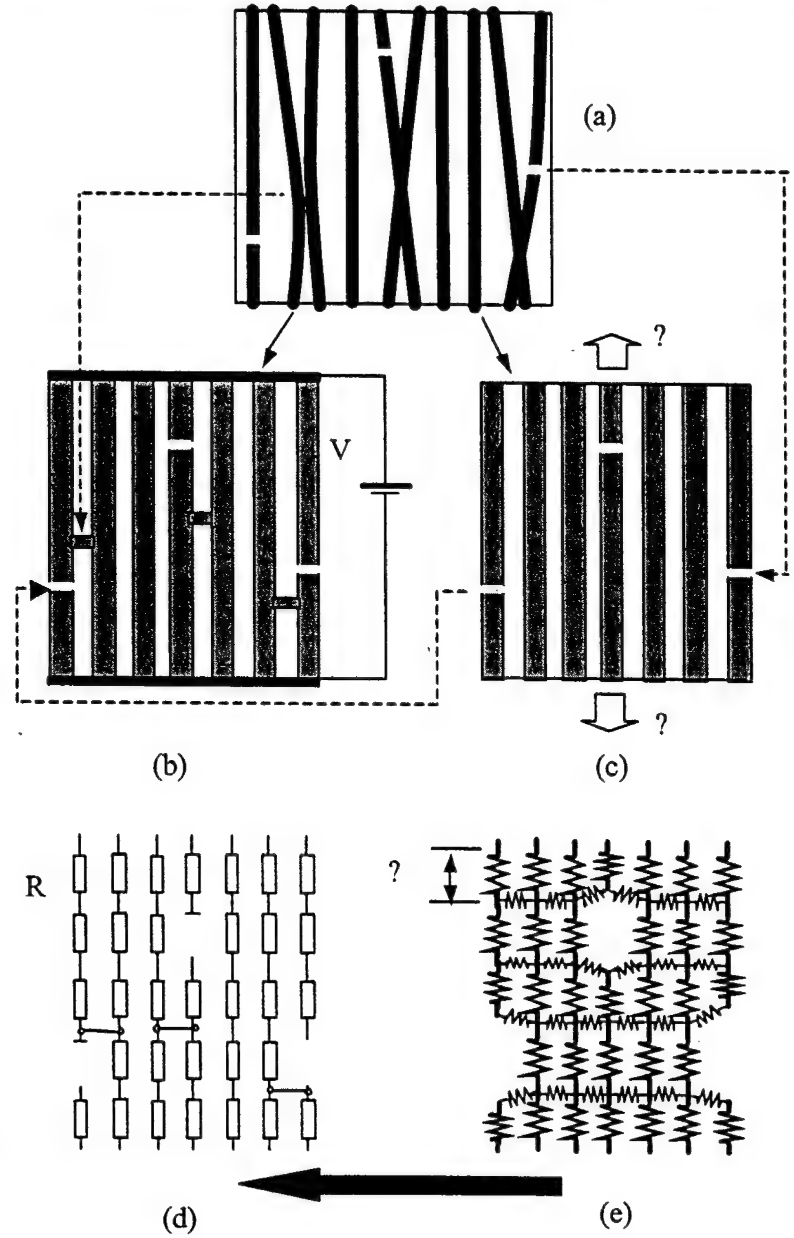
- What controls relationship between resistance and failure?
- How locally can damage be detected?
- How can signals be interpreted?
- How can this be used practically (outside the lab)?

Current effort:

Address some issues through computational modeling

Clearly need a coupled experimental effort

Coupled Mechanical, Electrical Models



Electrical Model:
Local resistances

Resistance vs.
stress/strain/damage

Mechanical Model:
Damage, local stresses

Stress vs. strain, failure

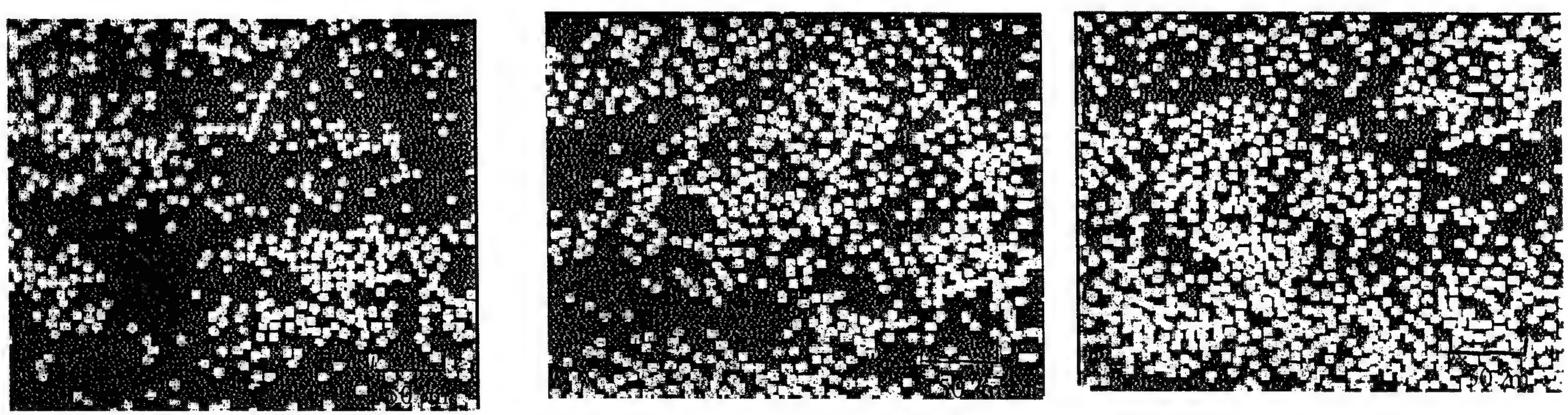
Length scales associated with fiber damage:

Old concept: Mechanical "ineffective length" $?_{c}$:

loss of load carrying capability depends on fiber, matrix, interface mechanical properties

New concept: Electrical "ineffective length" $?_{ce}$:

loss of current carrying capability depends on inter-fiber contacts, geometry, volume fraction

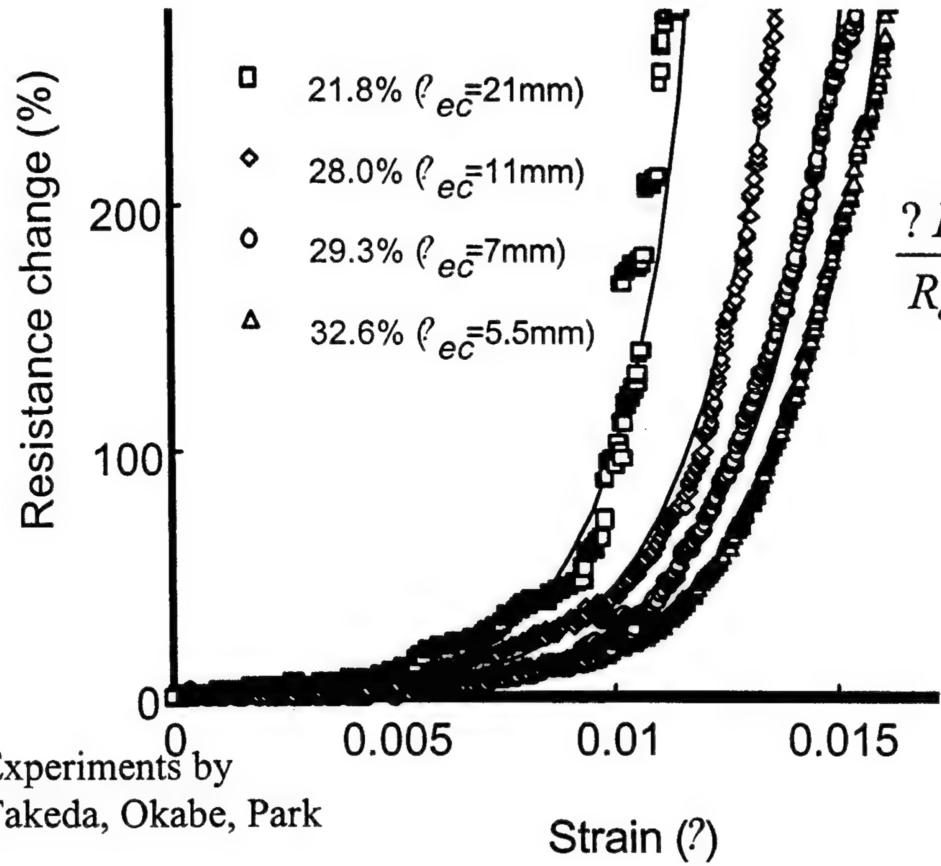


(a) $V_f = 22\ \%$ (b) $V_f = 28\ \%$ (c) $V_f = 32\ \%$

Modeling of Damage Detection by Electrical Resistance

Stochastic fiber damage + Mechanics Models + Electrical Models

✍ Mechanical damage & Electrical resistance predictions

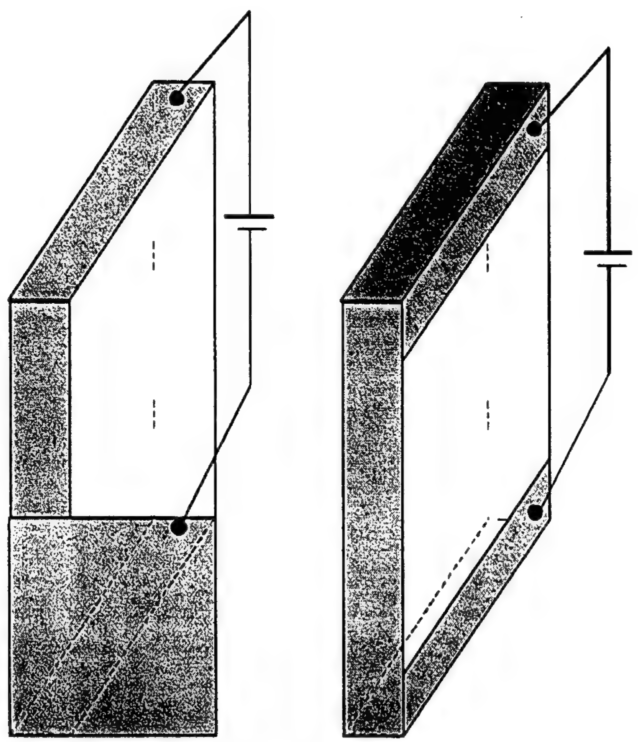


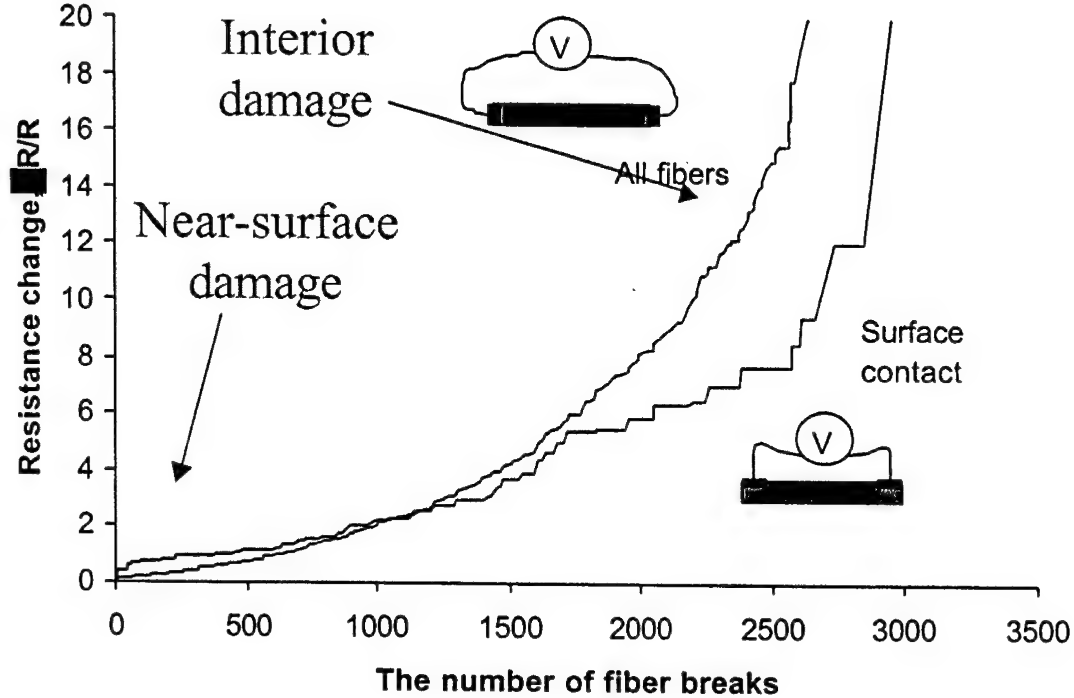
Experiments by
Takeda, Okabe, Park

$$\frac{?R}{R_o} ? (1? ??)\exp ?? \frac{?_{ec}}{?_c} ?? \frac{E_f ?}{?_c} ?^m ? \quad ? \quad 1$$

Known material parameters

How locally can damage be detected?



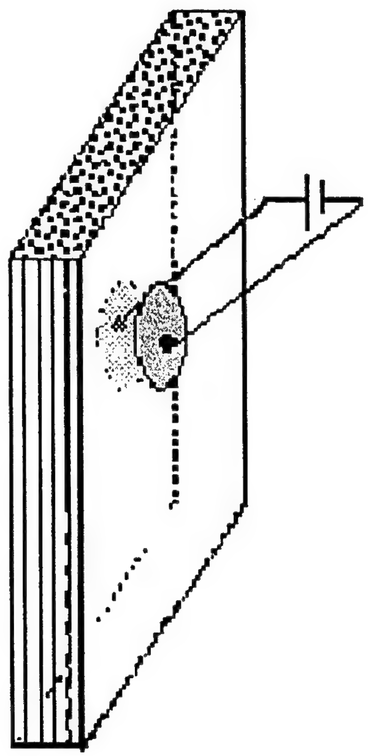


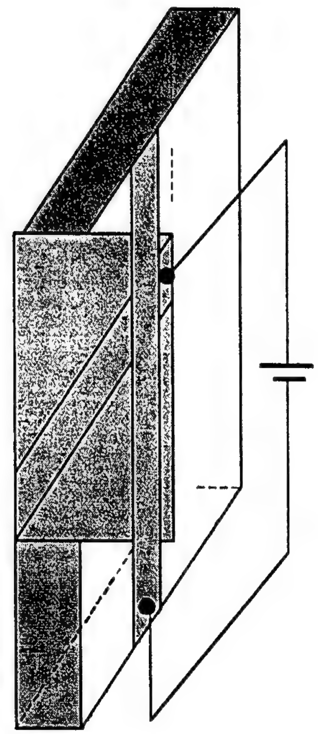
Damage sensing depends on Detection geometry

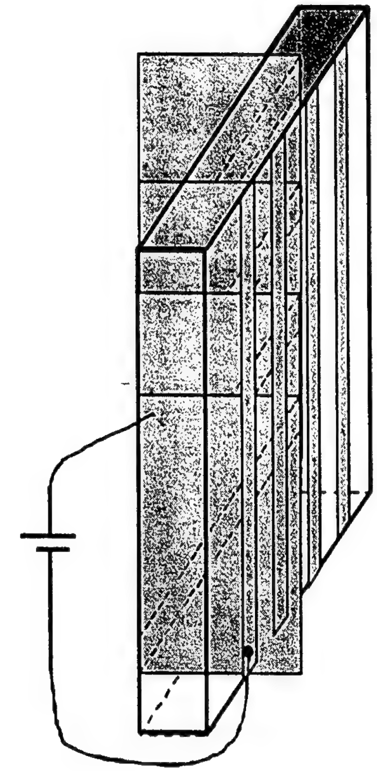
Design for LOCALIZED damage sensing

Sensing Depends on Detection Geometry

Detection Geometries to Measure Localized Damage



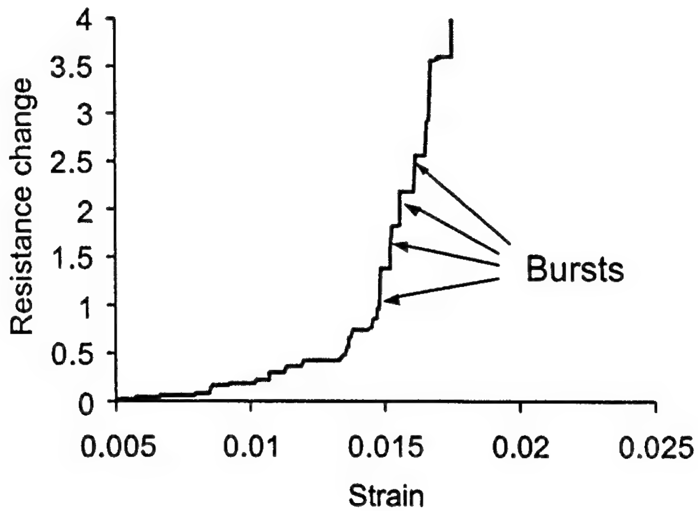


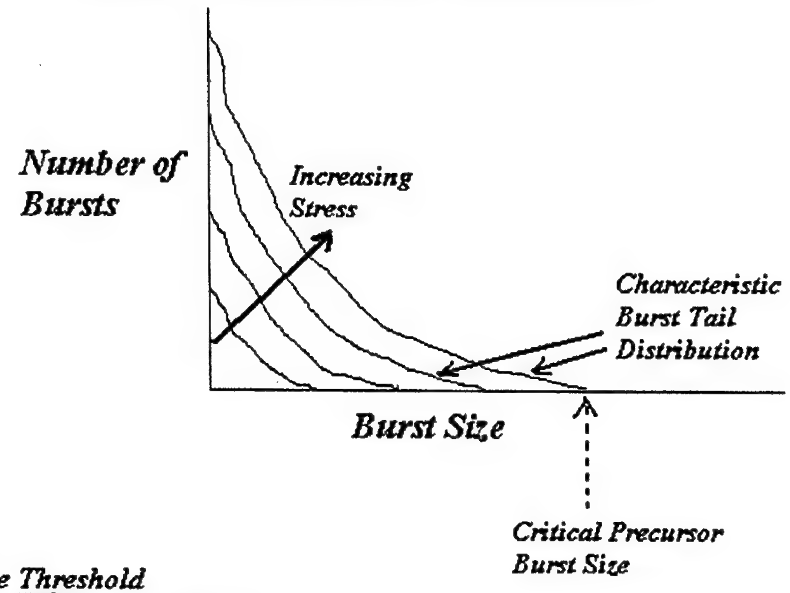


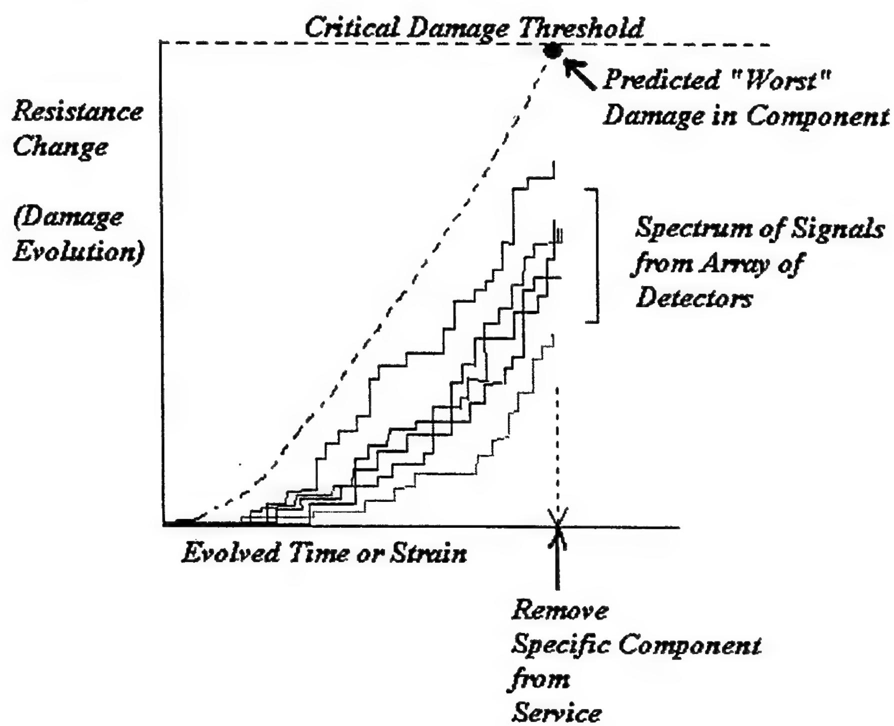
Use model to test simple geometries; determine spatial resolution

Realistic ply-level detection geometry

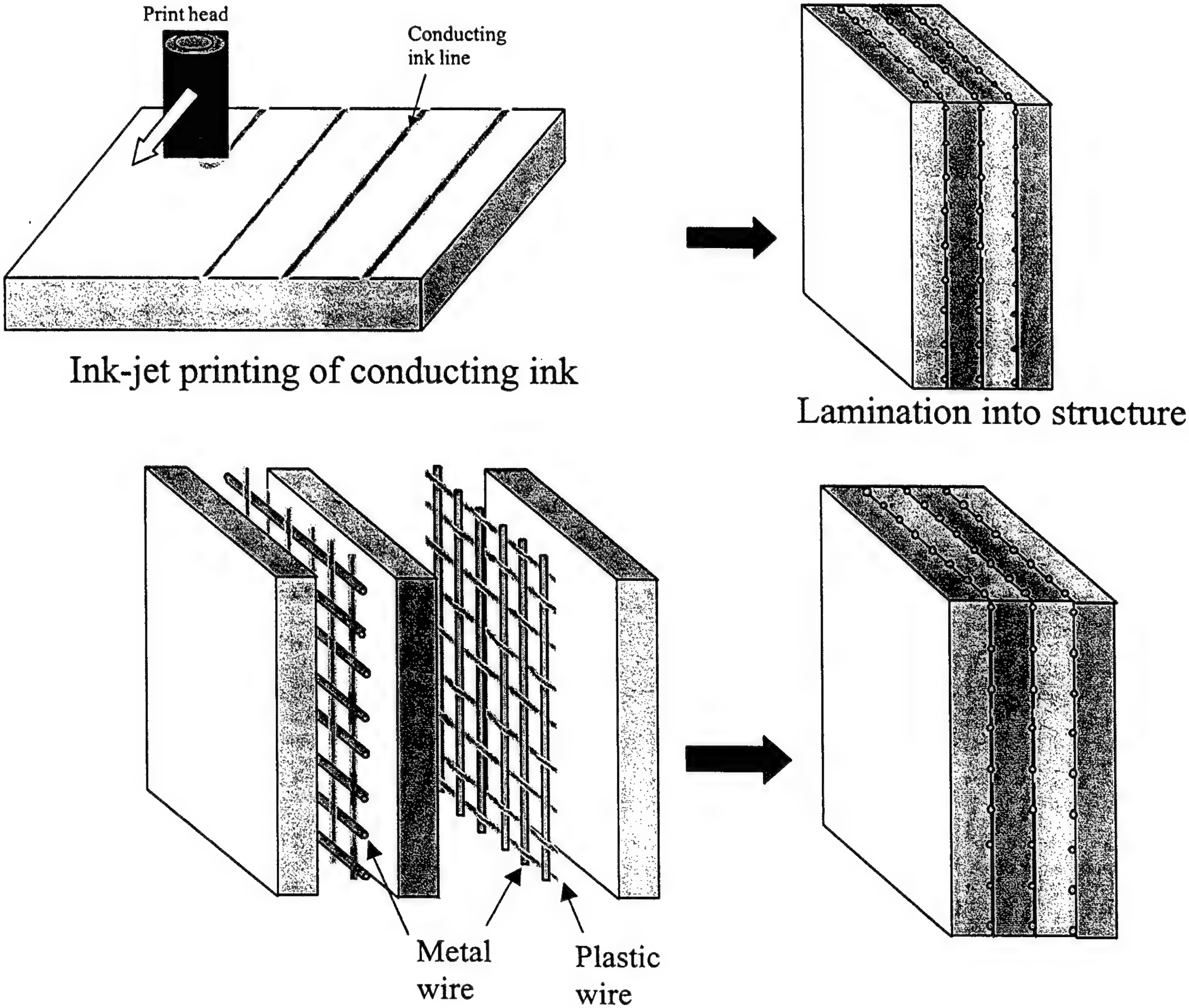
How can signals be interpreted? Need stochastic analyses







Feasible Fabrication of "sensor array"?



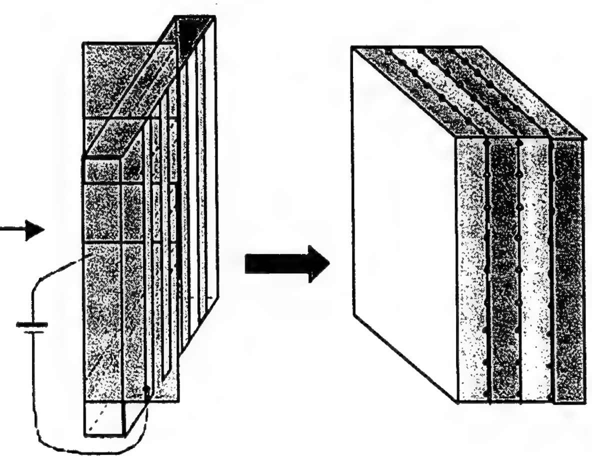
Innovation in Design:

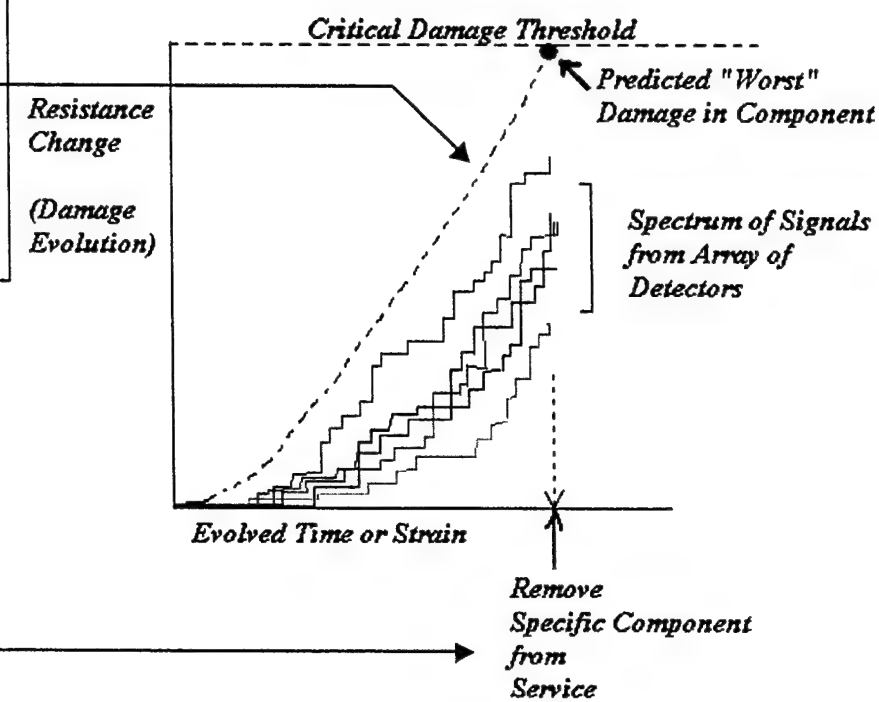
Design = Fundamental Materials Design

- Optimization of constituent materials for damage and sensing; control mechanical $?_c$ vs. electrical $?_{ce}$ characteristics

Design = Engineering Design

- Design of sensor arrays
- Design of sensor signal analysis
- Prediction of strength, life, reliability of in-service components





Demand and Challenges in Structural Health Monitoring

1st AIR FORCE WORKSHOP ON
"MULTIFUNCTIONAL AEROSPACE MATERIALS"
October 23-24, 2002, Purdue University, W. Lafayette, IN

Fu-Kuo Chang
Dept. of Aeronautics and Astronautics
Stanford University
Stanford, CA 94305

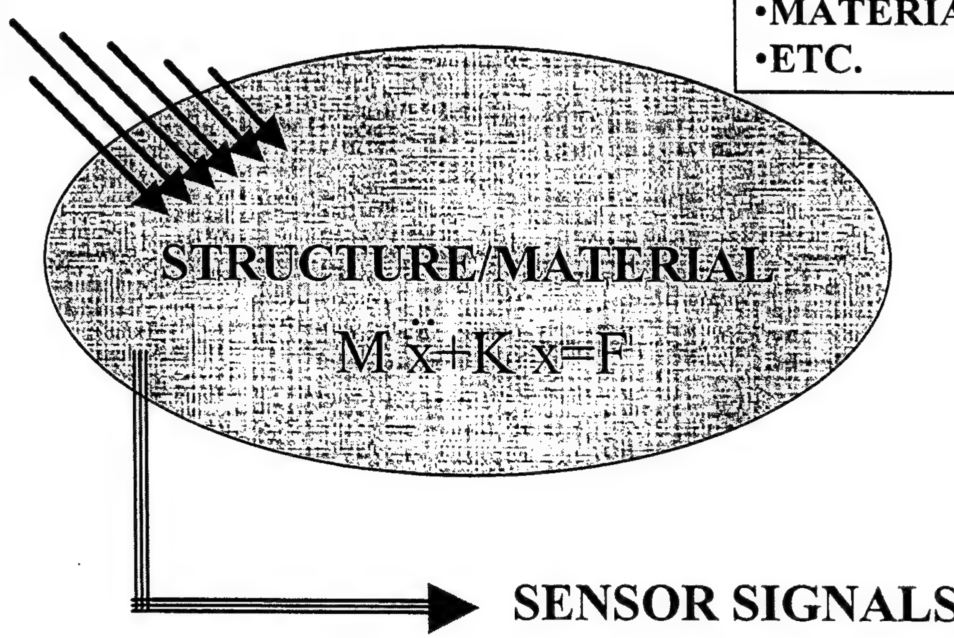
Problem Statement

GIVEN SENSOR MEASUREMENTS, DETERMINE EXTERNAL AND/OR INTERNAL PARAMETERS.

(NONLINEAR INVERSE AND NON-UNIQUENESS)

EXTERNAL:
- LOAD
- TEMPERATURE
- MOISTURE
- ETC.

INTERNAL:
- DAMAGE LOCATION
- DAMAGE SIZE/TYPE
- MATERIAL PROPERTIES
- ETC.



Sensors

- **PASSIVE** (receive signals only)
  - OPTICAL FIBER
  - STRAIN GAUGE
  - MICROELECTRONIC SENSORS
  - Etc.

- **ACTIVE** (receive and generate signals)
  - PIEZOELECTRIC MATERIALS
  - Etc.

PASSIVE SENSING

$$M\ddot{x} + Kx = F$$

Given $\ddot{x}$, $\dot{x}$, x

Determine

F (external loads, etc.)

ACTIVE SENSING

$$M\ddot{x} + Kx = f$$

Given $\ddot{x}$, $\dot{x}$, x, f (controlled input)

Determine

M(corrosion, degradation, etc.)

K (cracks, degradation, damage, etc.)

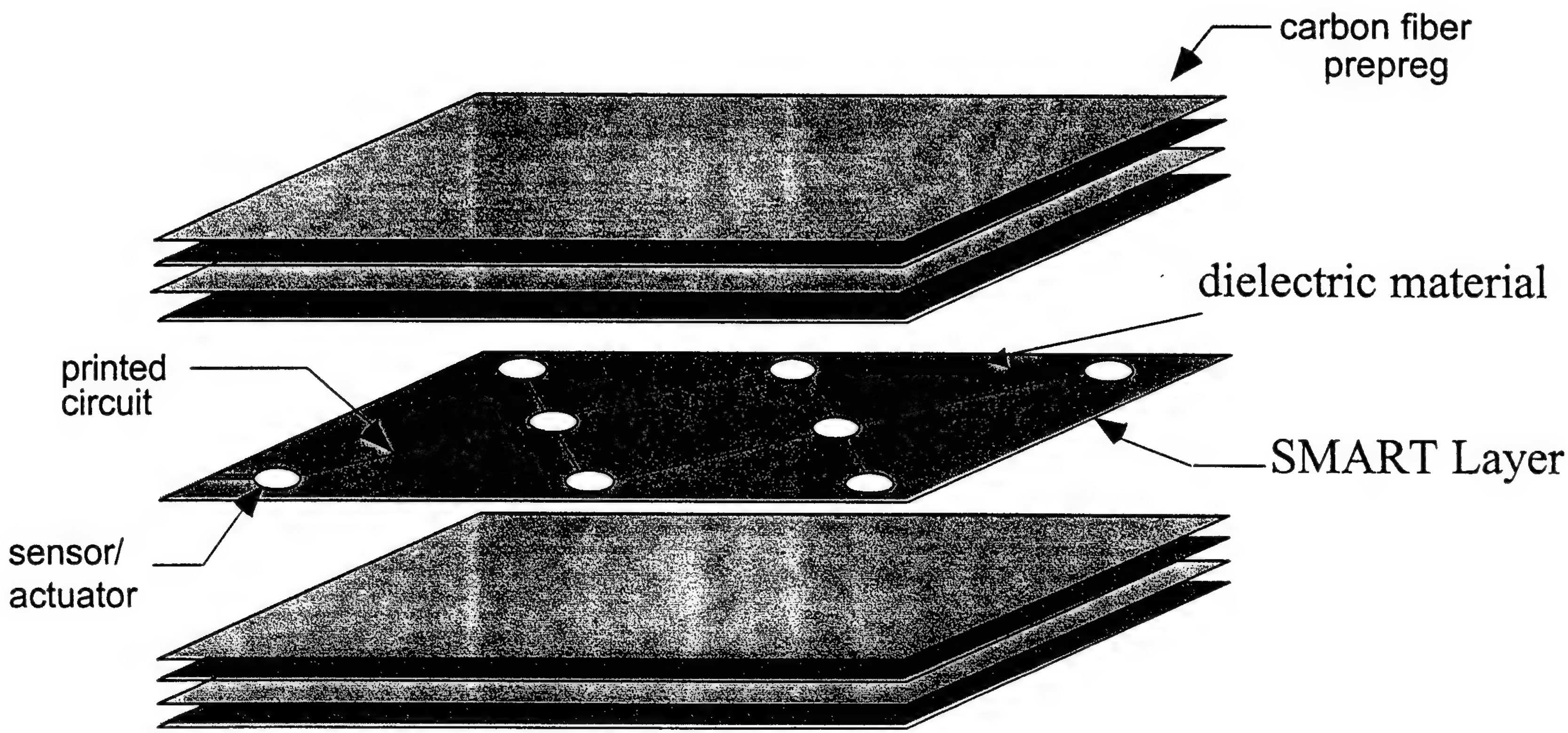
Technical Challenges

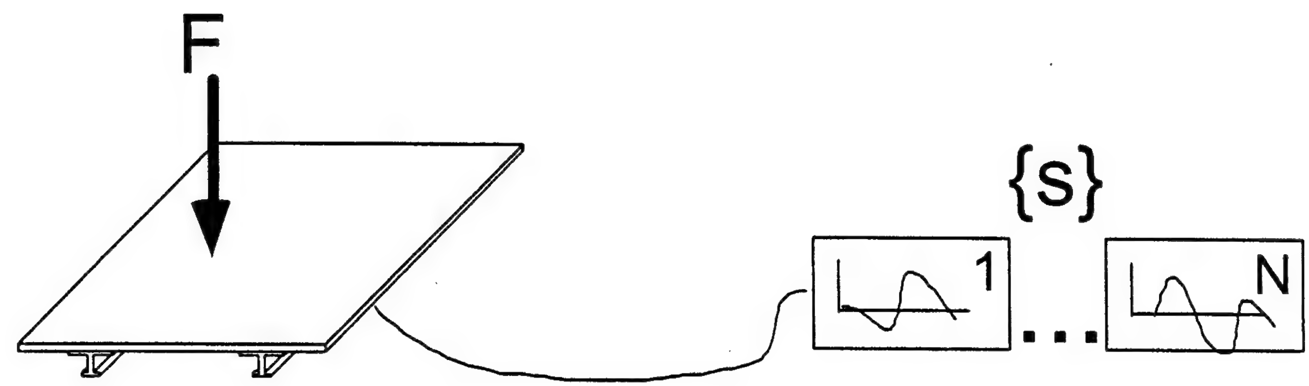
- **SENSORS**
- **SENSOR/MATERIAL INTEGRATION**
- **HARDWARE DESIGN/IMPLEMENTATION**
- **SIGNAL PROCESSING AND INTERPRETATION**
- **RESIDUAL STRENGTH AND LIFE PREDICTION**

Piezoelectric Sensor Network

SMART (Stanford Multi-Actuator Receiver Transduction) Layer

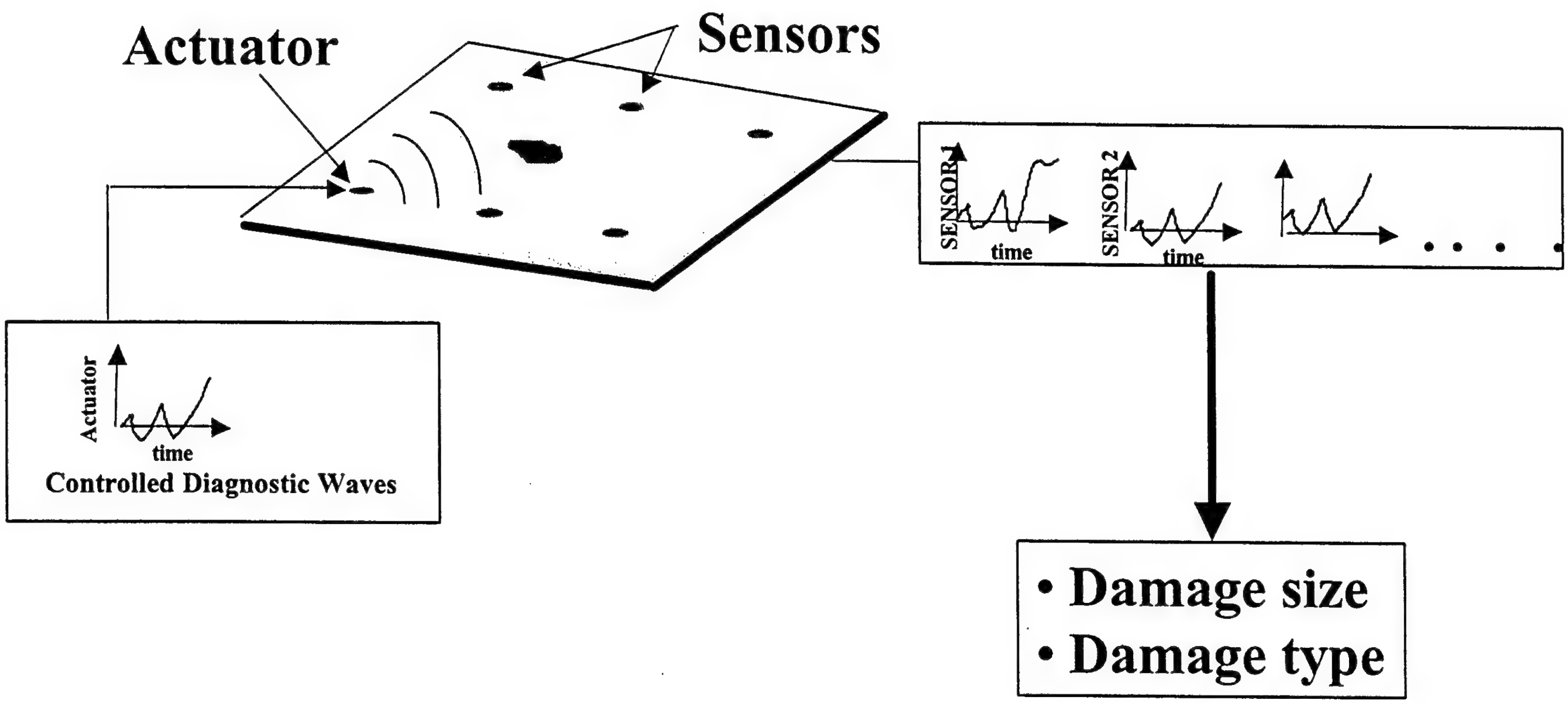
- FLEXIBLE PRINTED-CIRCUIT BOARD TECHNIQUE





- **Given: {s}**
  - Sensor data from impact on stiffened panel
- **Determine: F**
  - Impact location (x,y)
  - Impact force history f(t)

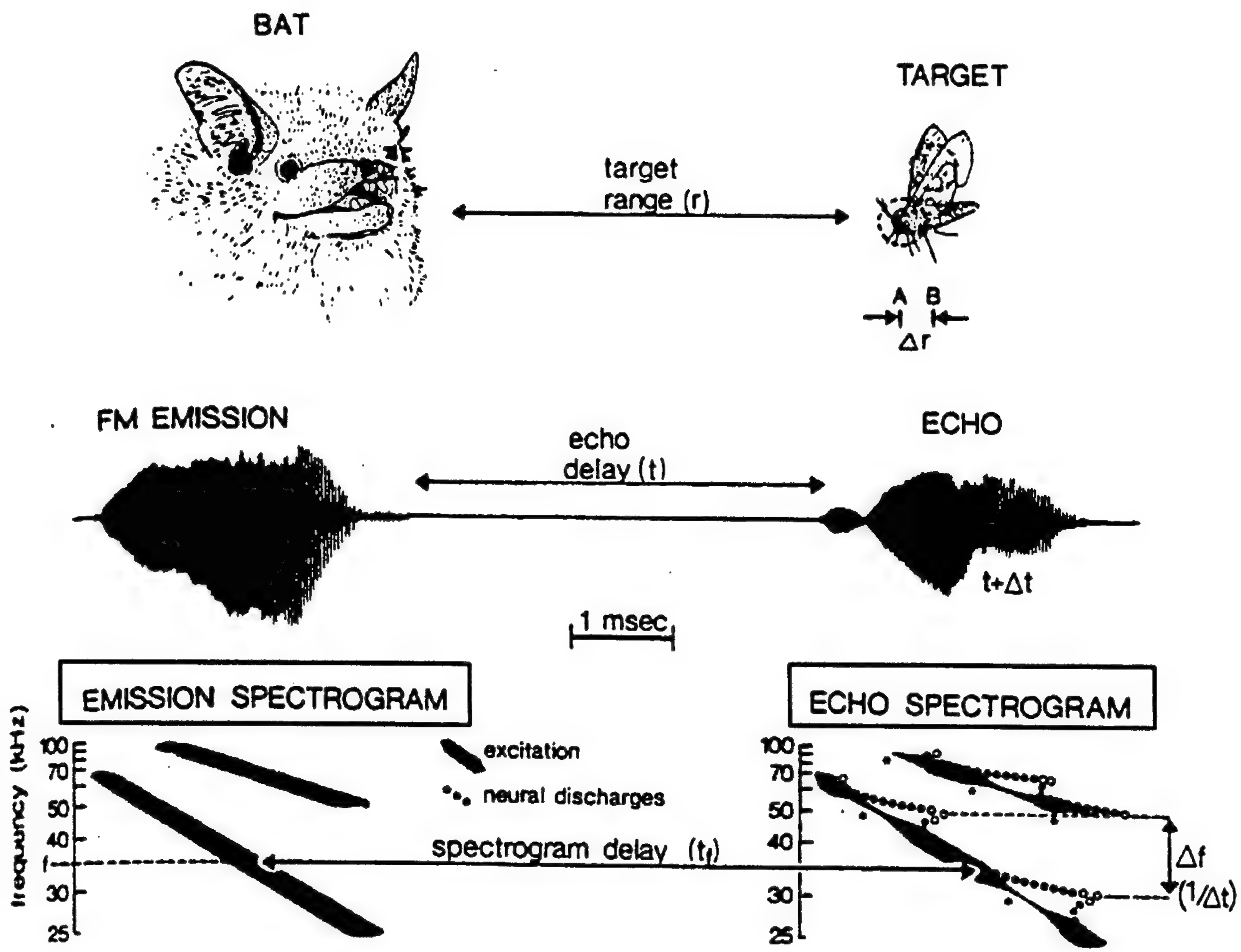
Active Damage Detection



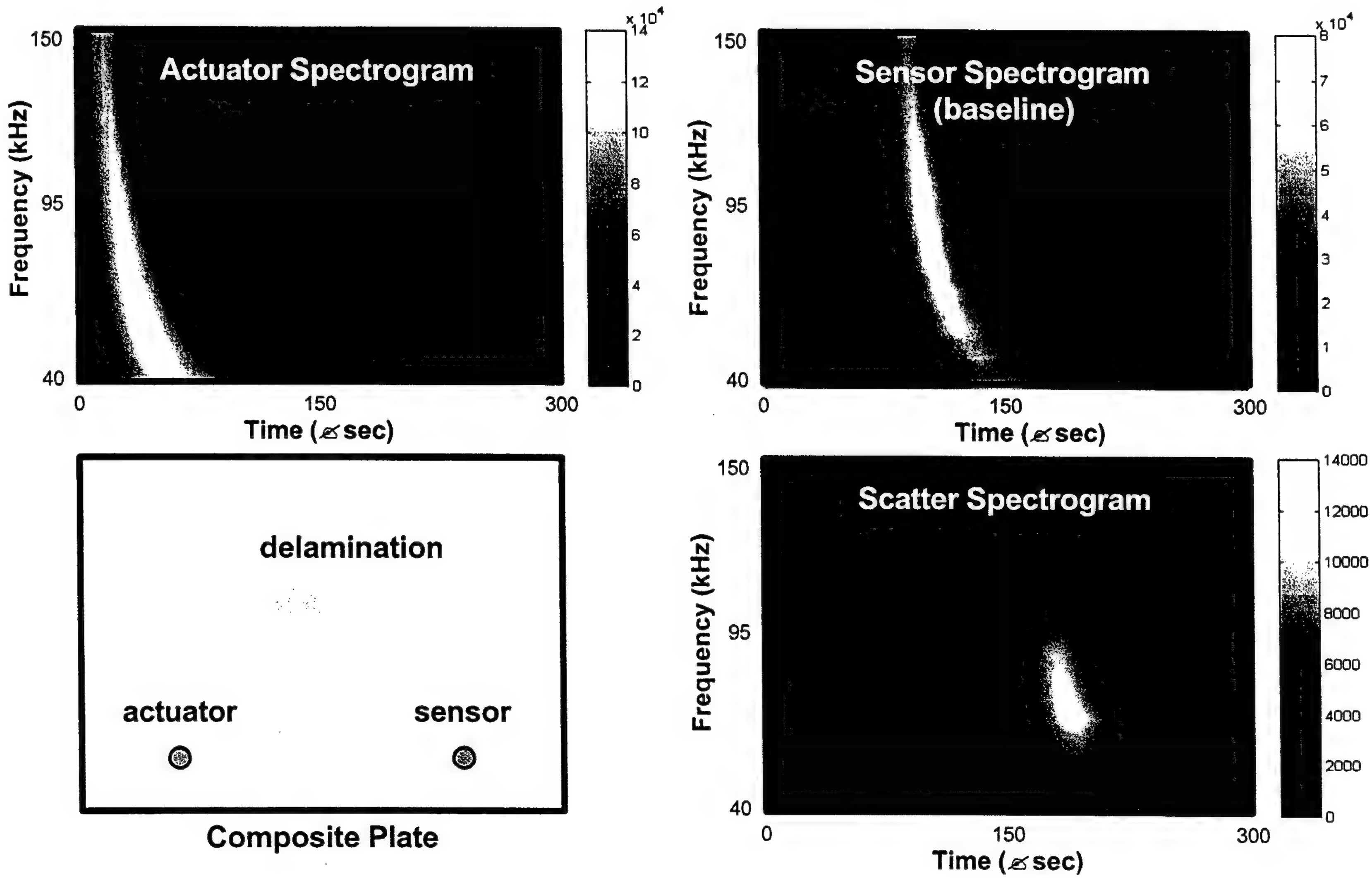
Bat Echolocation

- Bat uses time-of-flight for ranging.
- FM bats use frequency spectrum change for sizing.

From J.A. Simmons, et al,
J. Comp. Physiol. A (1990)
166:449-470

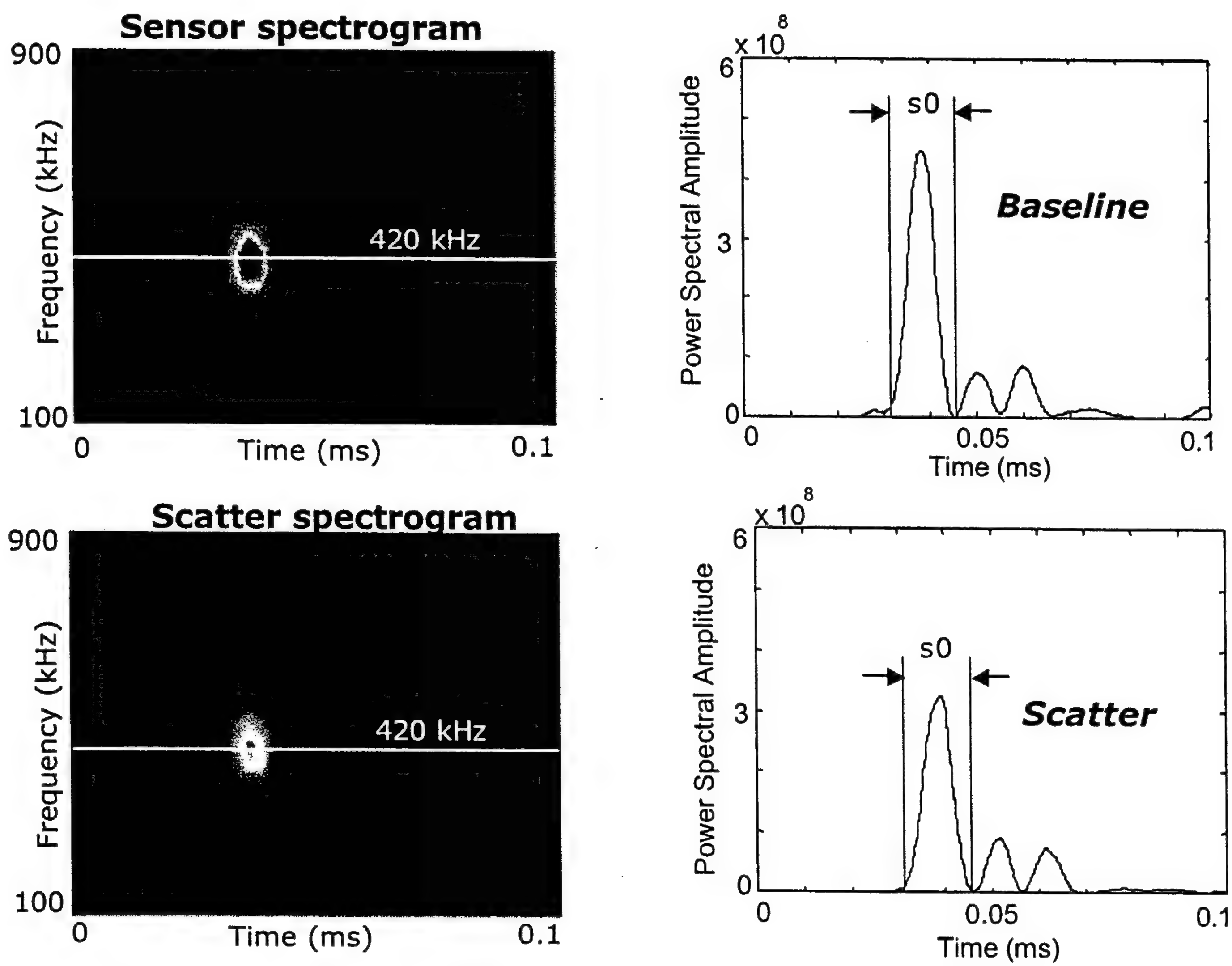


Spectrogram



QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Signal Processing

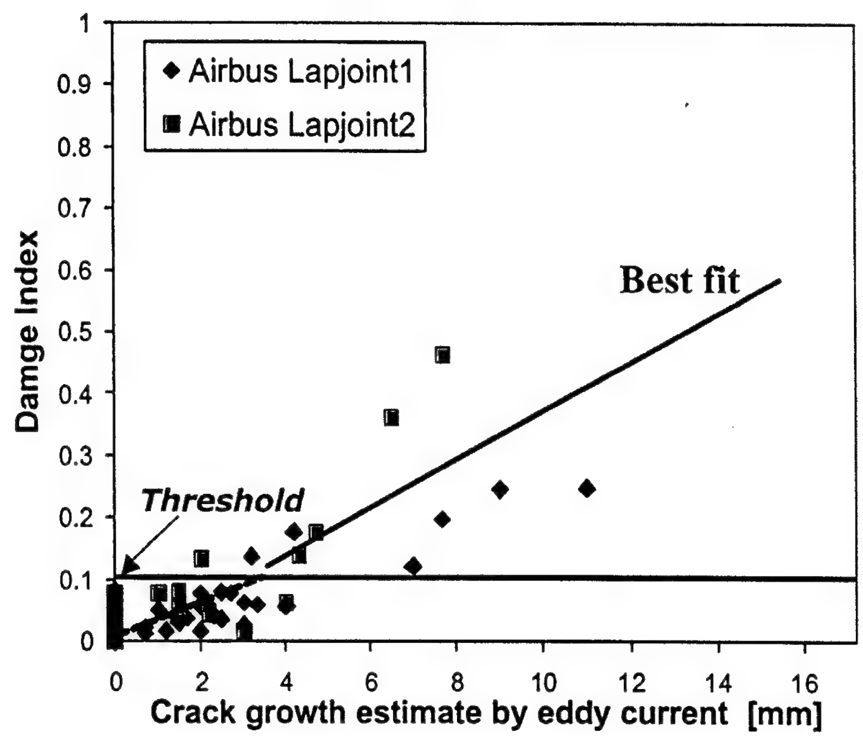


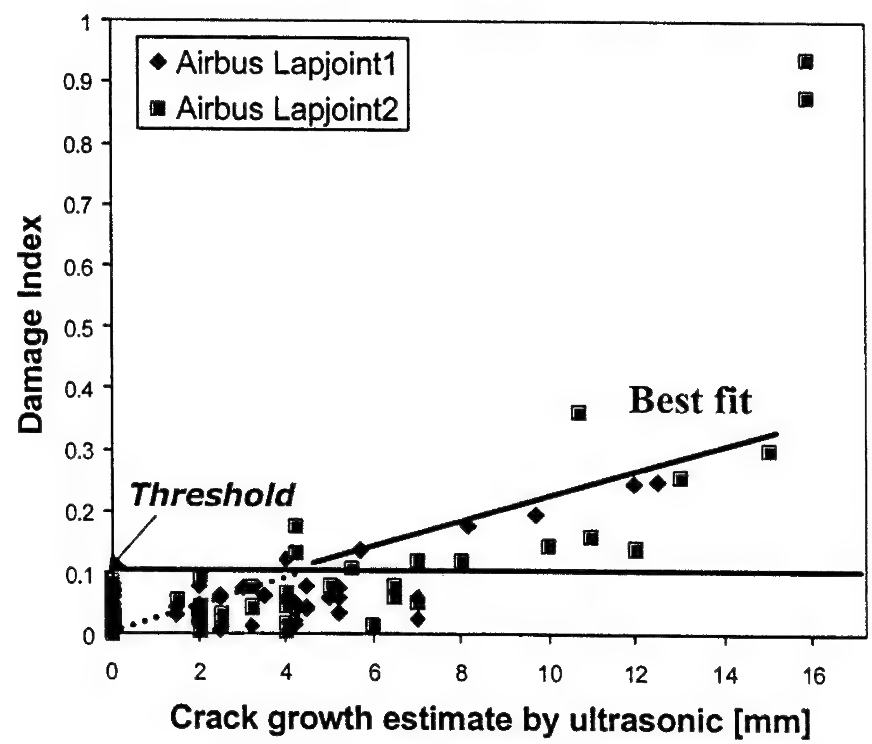
Interpretation - Damage index

- Damage Index $? \; ? \dfrac{\displaystyle ?_{t_i}^{t_f} |S_{sc}(?_0, t)|^2 \, dt}{\displaystyle ?_{t_i}^{t_f} |S_b(?_0, t)|^2 \, dt} ?^{?} \quad = \quad \left(\dfrac{\textbf{Scatter energy of s0 wave}}{\textbf{Baseline energy of s0 wave}} \right)^{a}$

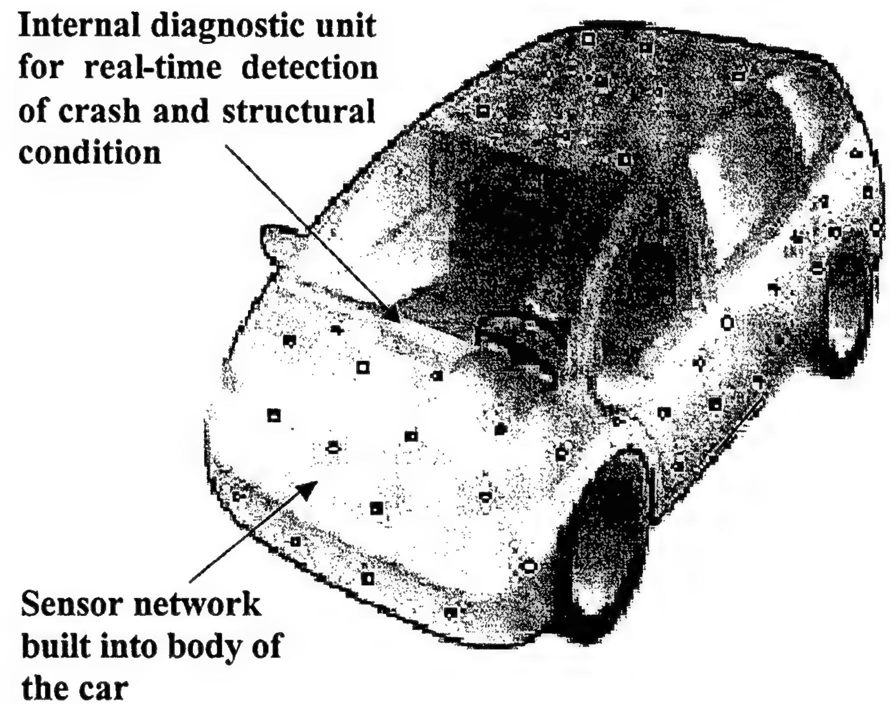
where
  a=0.5: gain factor, $0 ? ? ? 1$
  S_{sc} :STFT of a scatter signal
  S_b :STFT of a baseline signal
  t_i :lower bound of s0 wave packet in time domain
  t_f :upper bound of s0 wave packet in time domain
?? ???selected driving frequency
?

Damage Index of SHM vs. NDT



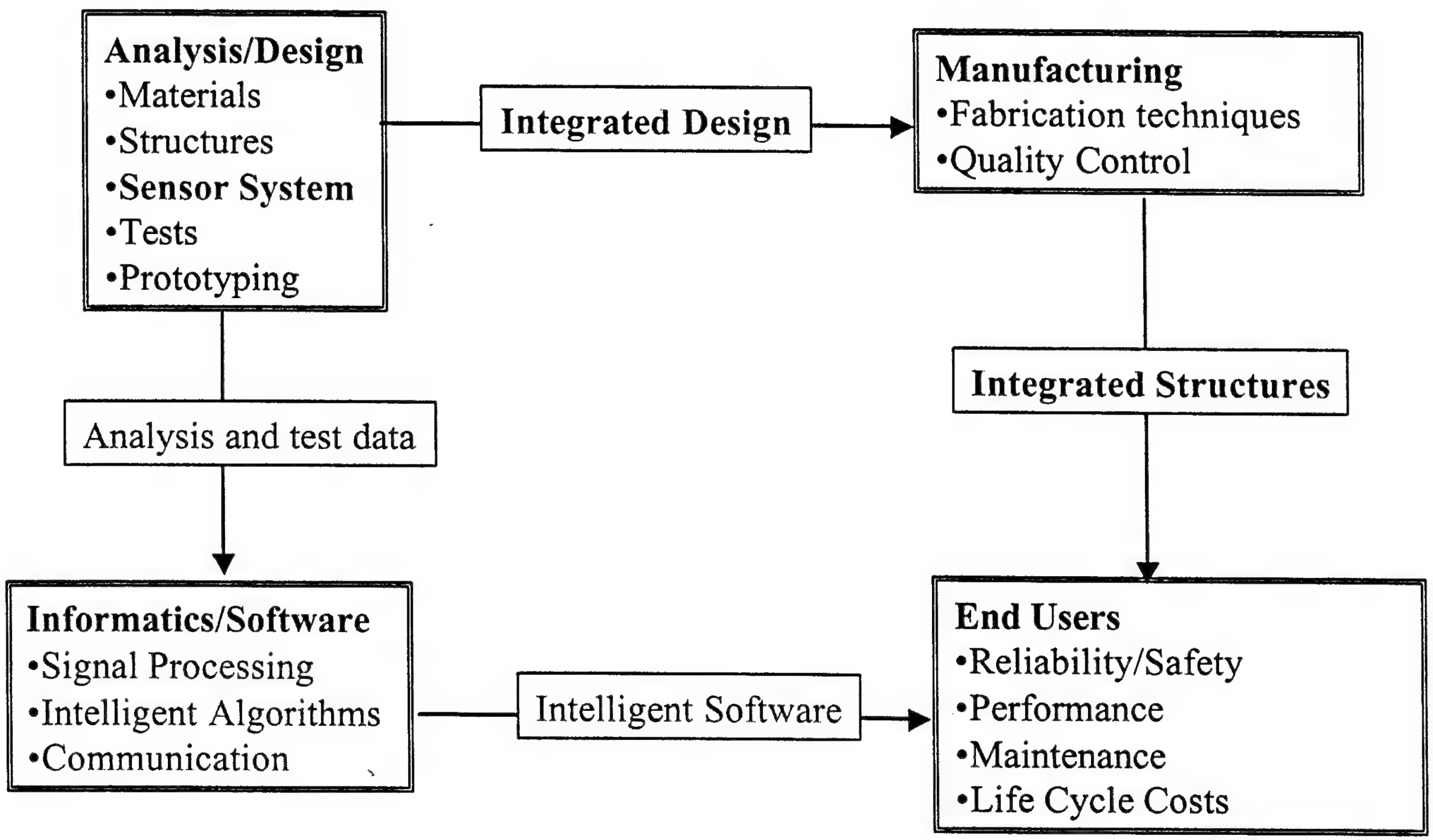


SHM System for Vehicles



- Condition Monitoring
- Crash Detection
- Active Suspension Control

SHM-based Structural Design Diagram



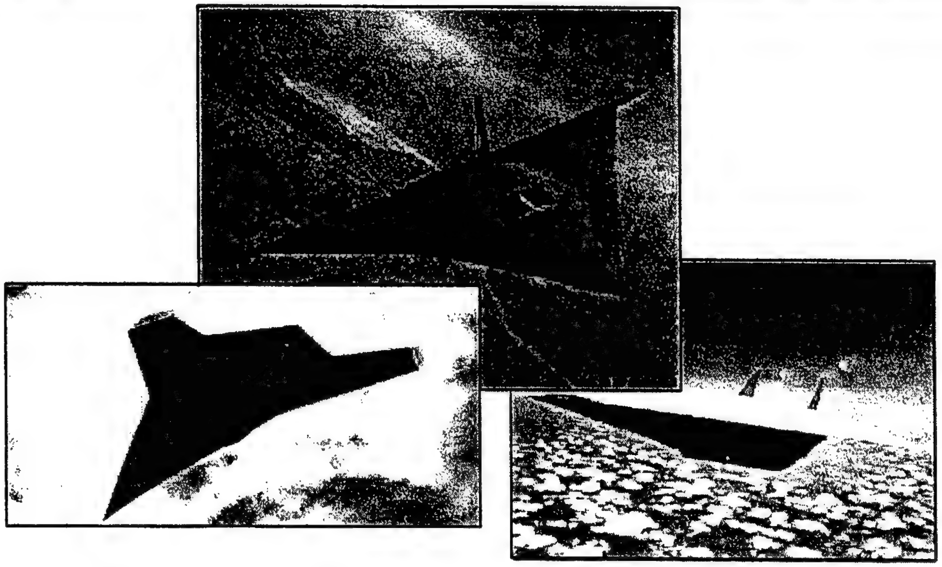
1st Air Force Workshop on "Multifunctional Aerospace Materials"

Oct 23-24 2002

Thermal Structures for High Speed Aircraft

David A Brown
Air Vehicles Directorate
Structures Division

Thermal Structures for Future High Speed Vehicles

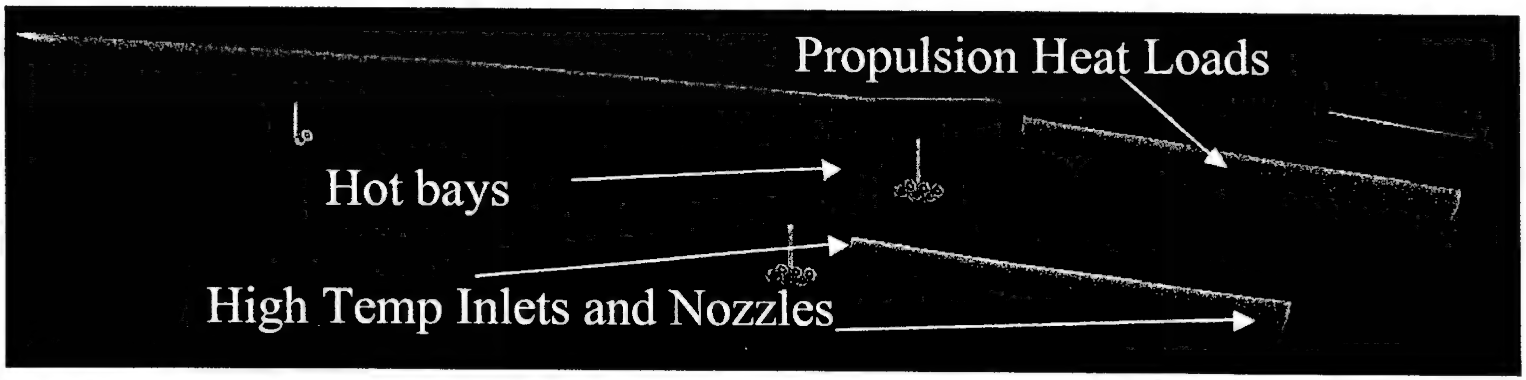


Current Air Force Studies
Evaluating Long Range
High Mach Vehicles

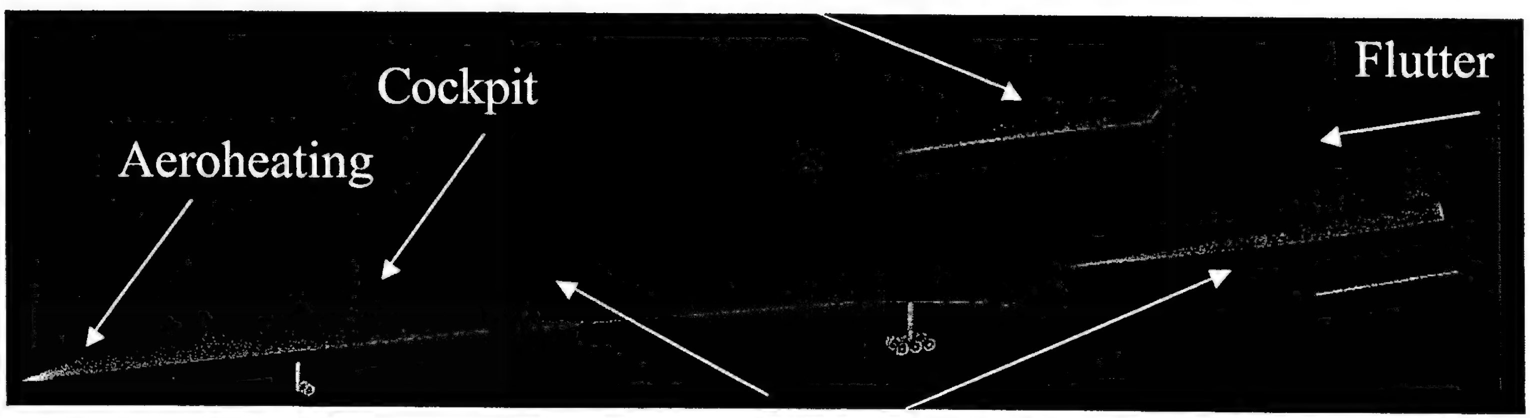
- Many Thermal and Structural Needs because of Aerodynamic and Propulsion Heat Loads
  - Material Compatibility
  - Lightweight High Temperature Structures
  - Insulation/Thermal Management
- Multifunctional Technologies may be Key to Lightweight Affordable Solutions

Thermal Structures for Future High Speed Vehicles

Mach 2-4 Conceptual Vehicle



Thin wings



High Temperature Fuel Tanks

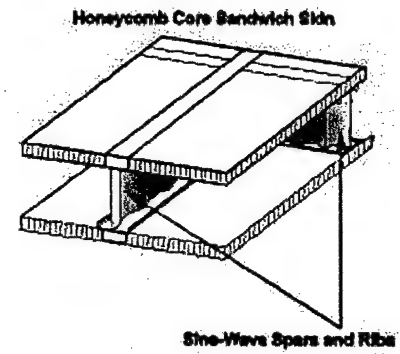
Structural Concepts for Consideration

- Unitized Structure
  - Integral Composites, Formed Metallic, Preformed Joints
- Smart Structures
  - Health Monitoring, Imbedded Sensors
- Adaptive Structures
  - Adaptive Leading Edges, Fuel Integration, “Morphing Technologies”
- High Temperature Metals & Composites
  - CMCs, Alum/Titanium,
- Structures/Propulsion/Subsystem Integration
  - Inlet, Engine, Nozzle, Integrated Subsystems
- Active/Passive Structural Cooling
- Advanced Analytical Techniques
  - MDO, Probabilistic Analysis

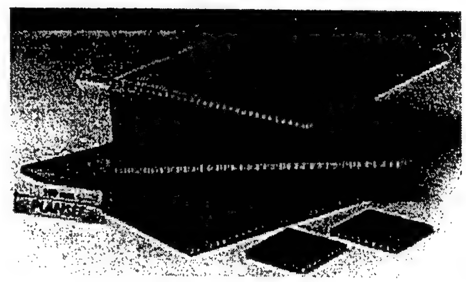
Multifunctional Structural Concepts for Future High Speed Vehicles

Potential Technology Options

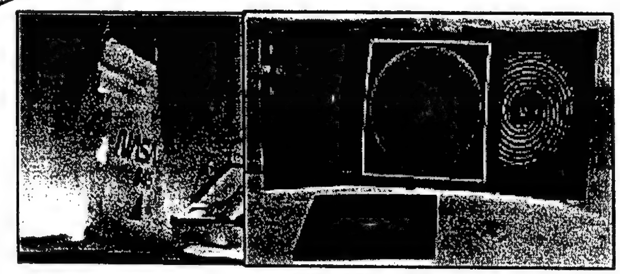
Compliant Understructure



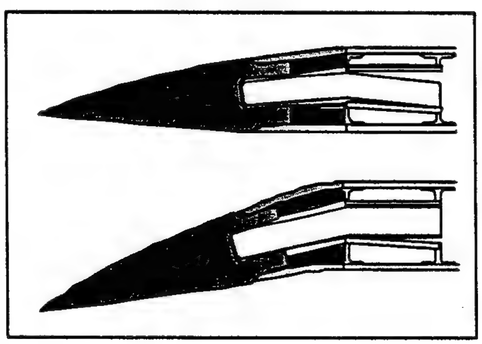
Lightweight Concepts

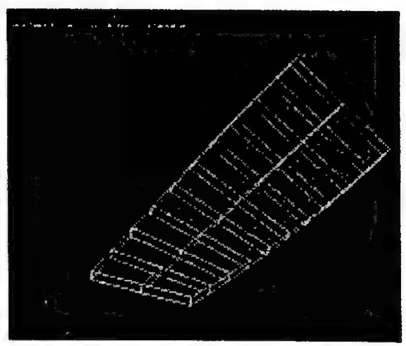


Antenna Integration

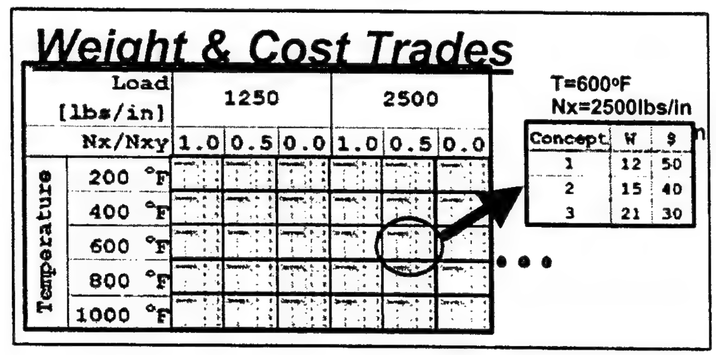


Adaptive Structure





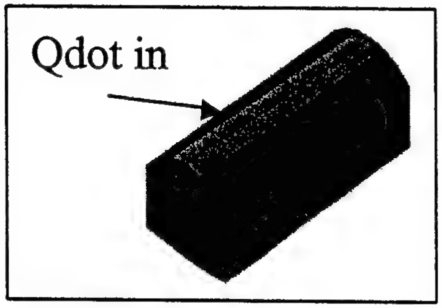
Optimized Design Methods



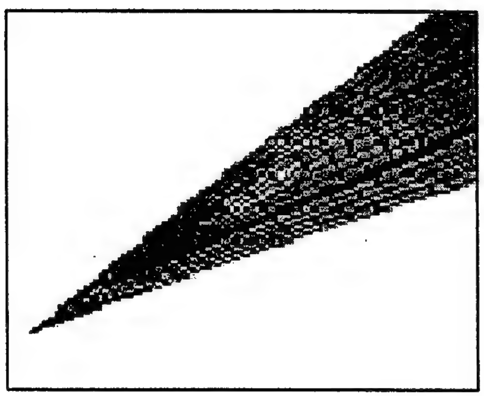
Thermal Management for High Mach Vehicles

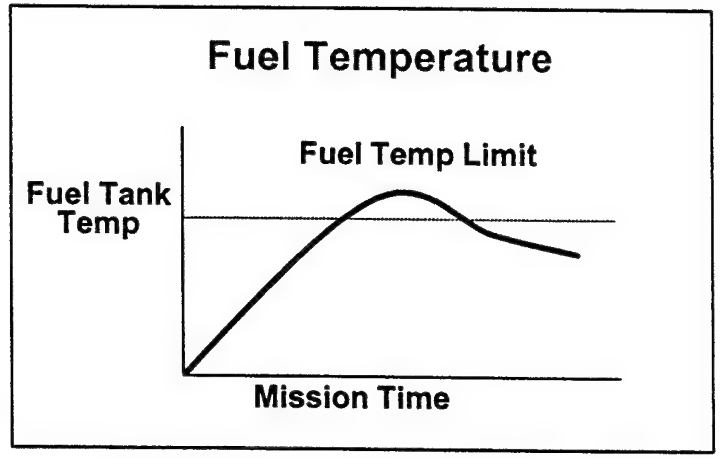
Aeroheating and Propulsion Heat Loads Drive Fuel Tank Temperatures

Fuel Tank Model



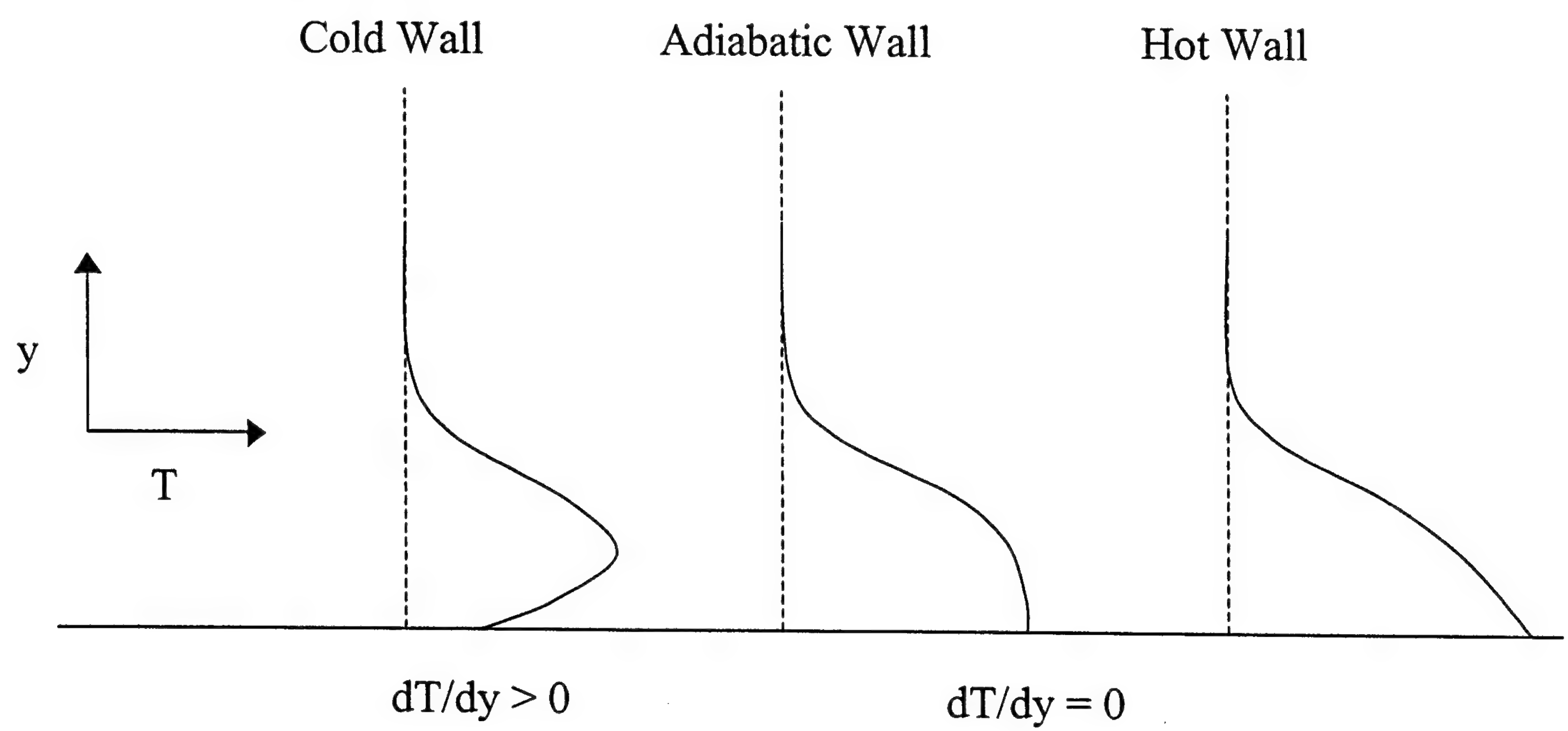
Aerodynamic Heating





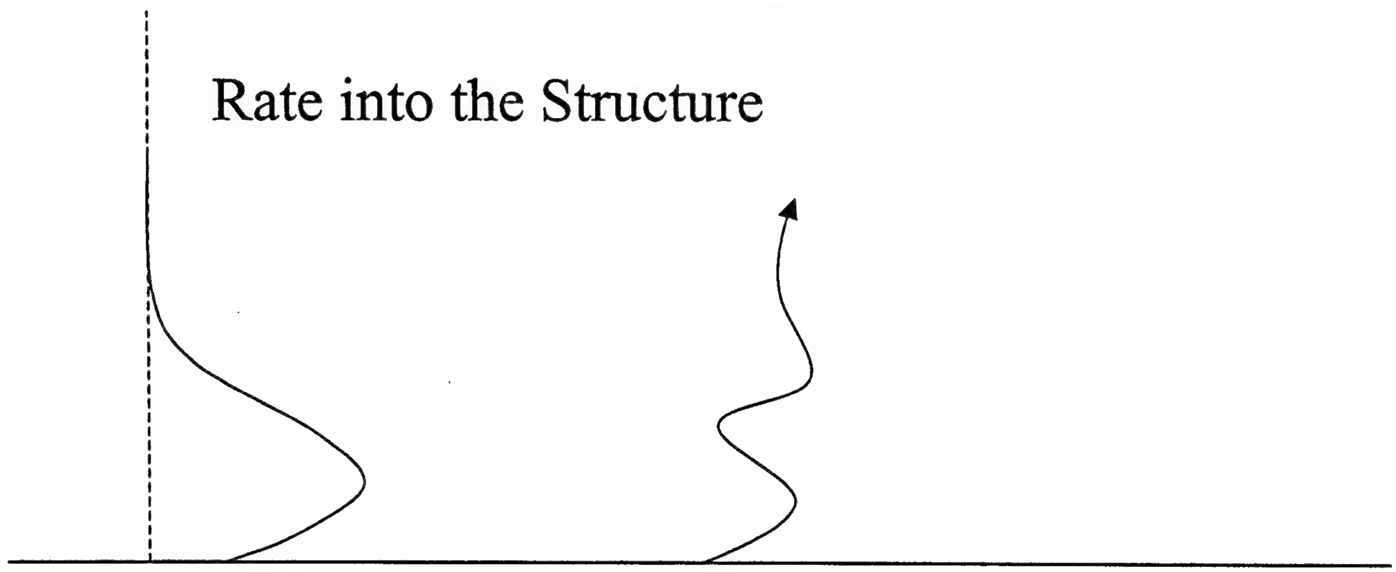
Boundary Layer Heat Transfer Rate to Wall

Depends on Wall Temperature for a Given Flow



Wall Heat Transfer Rate (BTU/ft^2-sec) = $Qdot_{con}$ = k*dT/dy, where k is air's thermal conductivity at the wall conditions, and dT/dy is the temperature gradient at the wall.

The Difference Between Convective and Radiative Heat Transfer Rates



$\downarrow$ $Qdot_{con}$ - $\uparrow$ $Qdot_{rad}$ = $\downarrow$ $Qdot_{str}$

$$Qdot_{str} = h^*(T_{adw} - T_w) - ??\,(T_w)^4$$

When $Qdot_{str}$ is 0 (insulated), T_w will equal the radiation equilibrium temperature, T_{RET}, otherwise $Qdot_{str}$ and heat capacity determine the rate of temperature change of the surface material.

Structures and Materials Key Technical Challenges

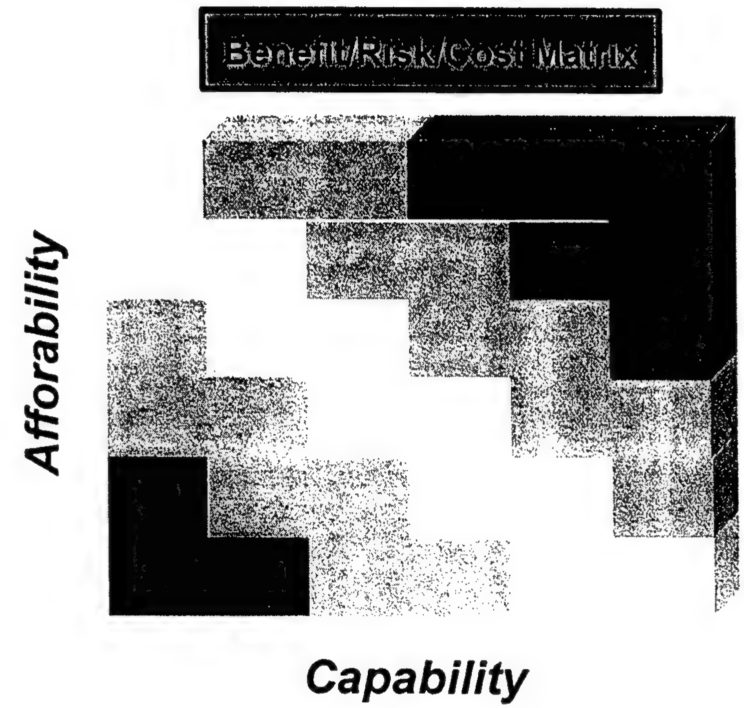
- Reduce Structural Weight Fraction (high temperature composites, Ti-Al, Al-Li Sandwich, composite landing gear, lightweight insulation, stitched composites, structurally integrated inlet and nozzle)
- Develop Structural Arrangements Capable of Surviving Extreme Aerodynamic and Propulsion Heat Loads (high temperature structures, ceramics, active/passive cooling)
- Insulate Subsystem and Critical Components from Aerodynamic and Propulsion Heat Loads (lightweight insulation, active cooling, coatings)
- Develop Optimized Design Methods Structural/Thermal/Aero (advanced design tools, load optimization, probabilistic methods, thin fuselage design)

Structures and Materials
Key Technical Challenges (Cont)

- Provide Adequate Heat Sink for the Aerodynamic and Propulsion Heat Loads (high heat sink fuels, high temperature seals, expendables)
- Develop Lightweight High Temperature Structural Arrangements (stiffness vs. thermal compliance, unitized structures)
- Provide Cooling to High Temperature Components such as inlets, nozzles, propulsion components, generators (high temperature lightweight heat exchangers, fuel-air heat exchangers)
- Minimize Aeroheating and Propulsion Heating to Vehicle Components (high emissivity coatings, high performance insulation)

Technology Risk Elements

- Performance
  - How difficult is the technology to mature ?
  - What is the probability of failure?
  - What is the impact of failure to the related system?
- Schedule
  - Can the technology be matured? When?
- Cost
  - What is the ROM cost to mature the technology



Summary

- Long Range High Mach Vehicles have Unique Structural and Thermal Requirements
  - ? Multidisciplinary Interactions Require New Solutions
  - ? Multidisciplinary Tools Needed
  - ? Multifunctional Concepts Needed to Meet Weight and Affordability Objectives

AFRL/MLB
OMC Thermal Management
&
Leading Edge Thermal Protection

24 Oct 2002

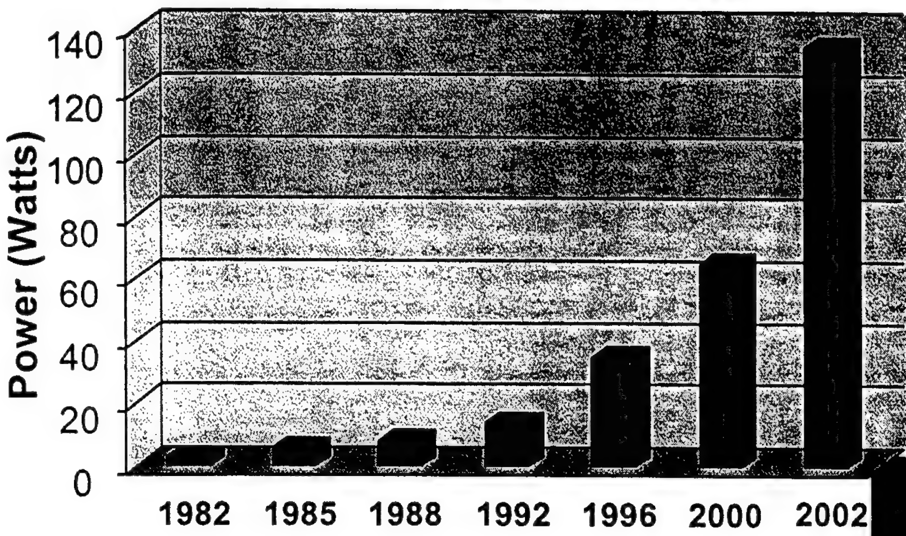
Keith B. Bowman, Ph.D., P.E.
(937) 255-9076
keith.bowman@wpafb.af.mil
Air Force Research Laboratory

Agenda

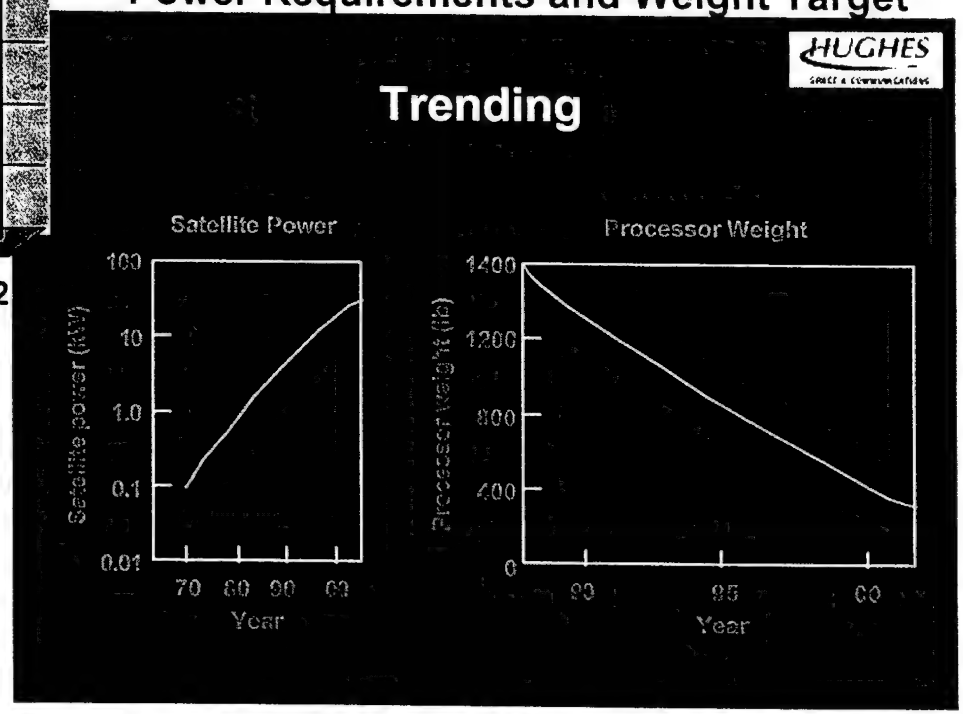
- Overview
- Thermal Management for Air Applications
  - Historical
  - Present
  - Planned
- Thermal Management/Protection for Space Applications
  - Historical
  - Space Operations Vehicle
  - Present
  - Planned
- Summary

Thermal Management Requirements

The "Why" Chart



Power Requirements and Weight Target



Thermal Management Needs and Solutions

Electronic Push

Increased communications, and electronic capabilities (Directed Energy/Microwave ect.) More chips require more cooling.

→ Waste heat can be dissipated using advanced materials. 2 to 4 times better than copper.

Component Strength/Capability

With the number of systems on aircraft/spacecraft increasing, consolidation of capabilities and space become imperative.

→ Lightweight, stiff components can be designed/build out of Advanced Materials offering high performance.

Compact/Size

Efficient use of space/resources is becoming more critical. Upgrades in capability result in more equipment stuffed into space it was not designed for.

→ Carbon based Materials (foam and Pyrolytic graphite etc..) can move more heat per unit area/unit density hands down.

Retrofitting

Aging aircraft are upgraded and augmented with new components requiring creative design and compromises.

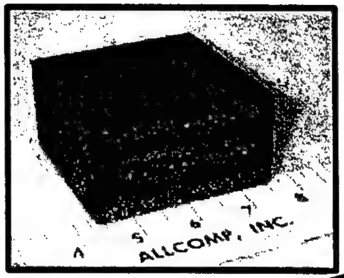
→ Advanced materials offer new opportunities/possibilities for higher performance retrofit components and systems

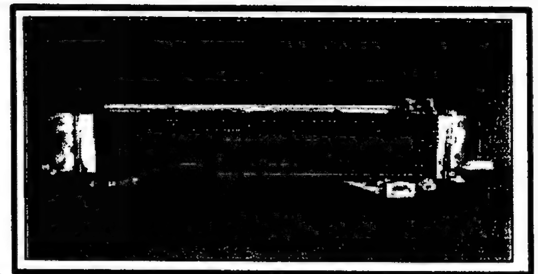
Less Maintenance

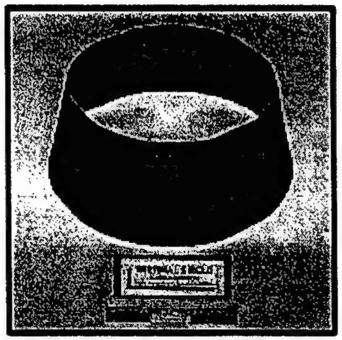
Less costly Logistics will always be an issue. Operational cost far outweigh any other phase of the Acquisition Lifecycle.

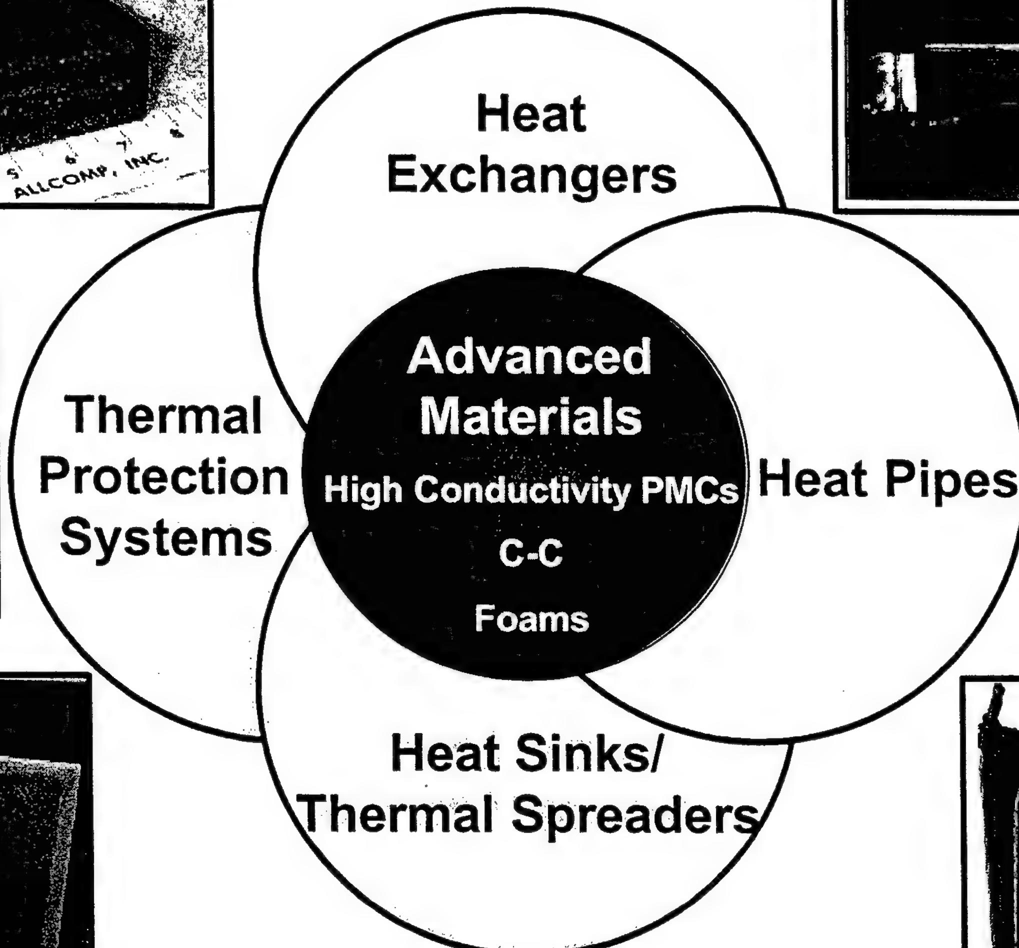
→ Considering lifecycle cost and lower operational temperatures, advanced materials can/will deliver lower logistical costs.

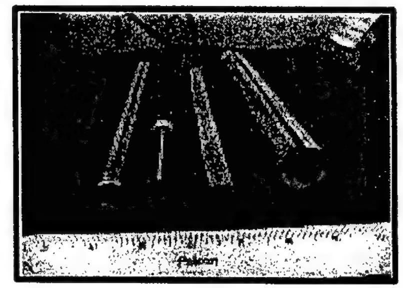
Thermal Management Applications

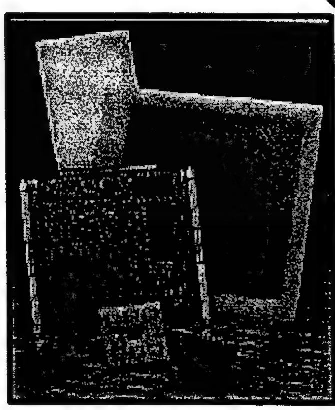


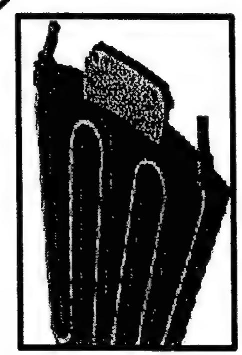








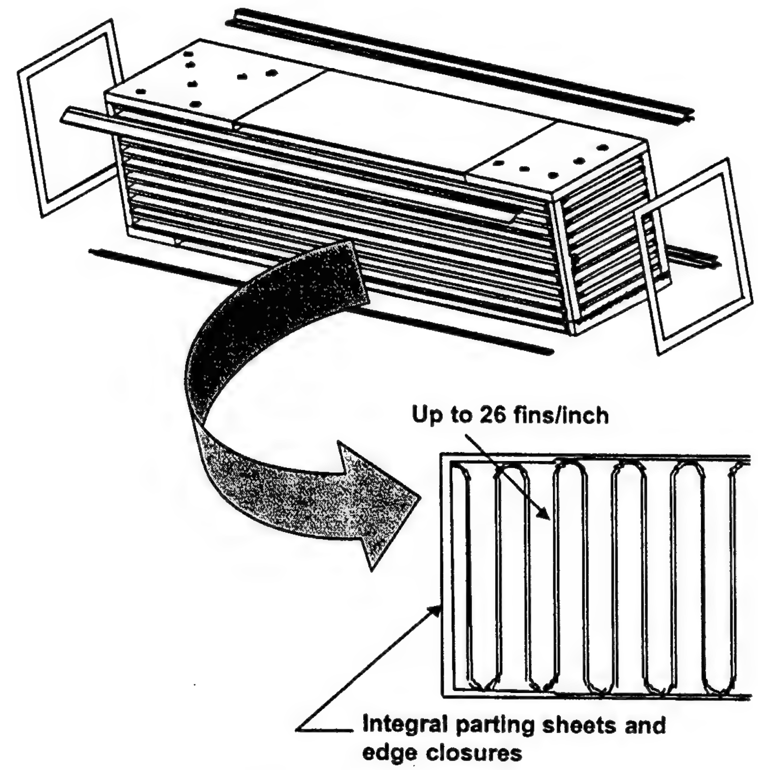


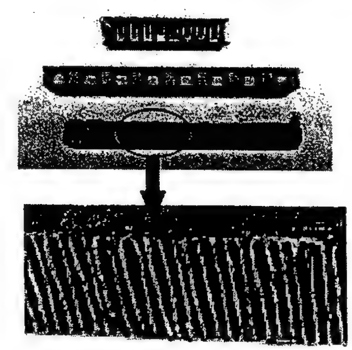



Thermal Management for Aircraft Applications

Past Effort:
C-C Heat Exchanger

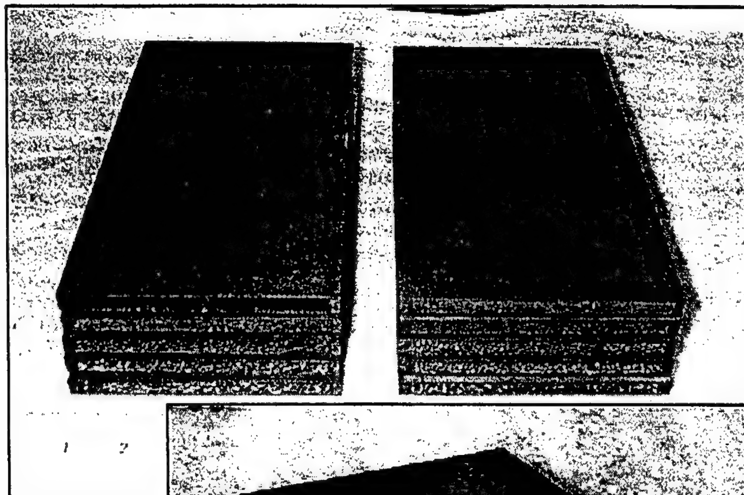
- Program initiated July 1996 in AFRL/VA with tech support from AFRL/MLBC.
- Objective:
  Development/fabrication/demonstration of affordable lightweight, C-C F/A-18E/F primary heat exchanger with 6000 hour service life goal
- Design of C-C HX Core completed with better predicted results than metallic designs
- Methods to form thin-wall, high density fins per inch successfully developed
- Two designs resulted assembled using a BNi-5; Ni-19Cr-10Si (liquidus 2075°F) braze
  - Integral - layers fabricated using CVD C-C processing
  - Conventional - layers fabricated by brazing component
- Oxidation protection needs further work
- Impetus for contracts looking at one-step C-C processing and oxidation protection

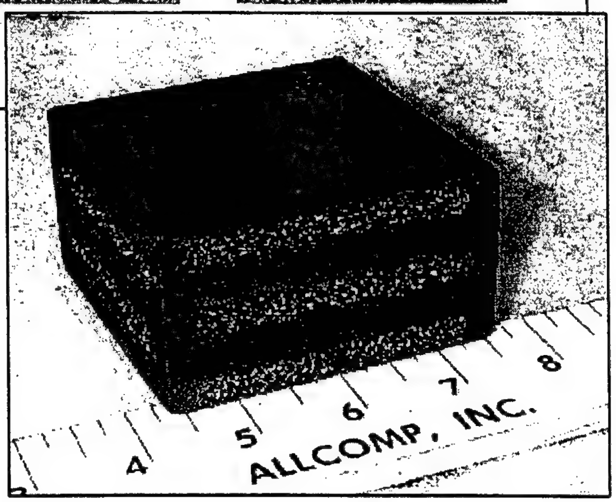




Current Program:
Carbon Foam Heat Exchanger

Next Generation Heat Exchanger - Carbon Foam





Coordination with Navy
Advanced Concept

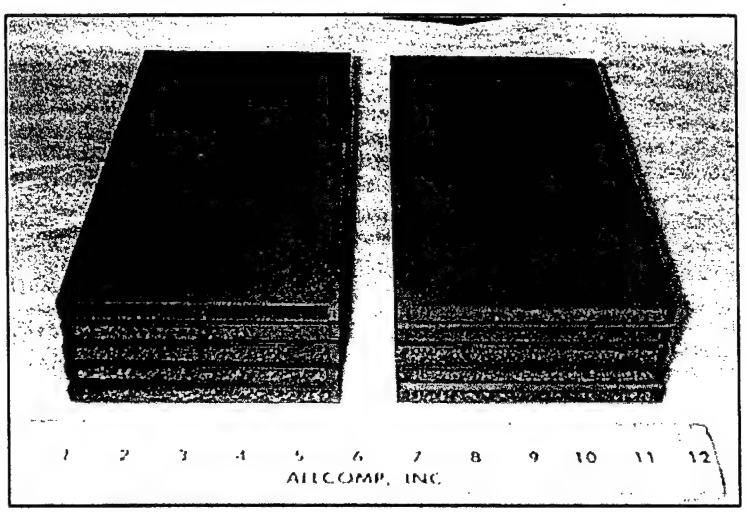
- Develop extremely light-weight, high conductivity composite V-22 heat exchangers
- Design and fabricate full size heat exchanger to decrease volume/increase cooling capacity
- Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
- Extends time between failure by at least 2X
- Extend range due to 70% weight reduction and
- Increase heat exchanger efficiency by 25%
- Increase heat transfer coefficient, h by 5X

Future Program: Carbon Foam Primary Heat Exchanger

Next Generation Advanced Heat Exchanger - Carbon Foam

- Build from previous efforts in
  - Carbon foam (Hi-K, graphitic)
  - Carbon foam heat exchanger
  - Oxidation protection (temps greater than NAVY SBIR)

- Design and fabricate full size heat exchanger (JSF??)



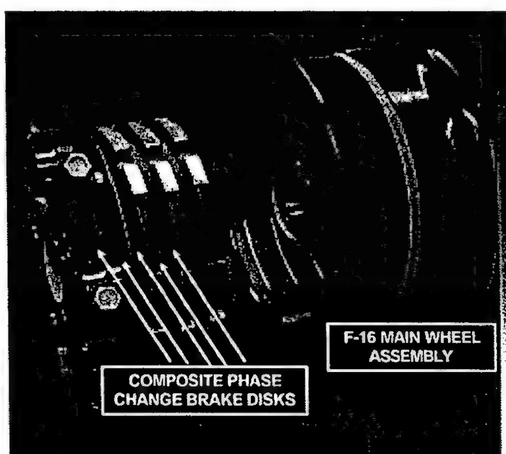
- Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
- Extends time between failure by at least 2X
- Extend range due to 70% weight reduction and
- Increase heat exchanger efficiency by 25%
- Increase heat transfer coefficient, h by 5X

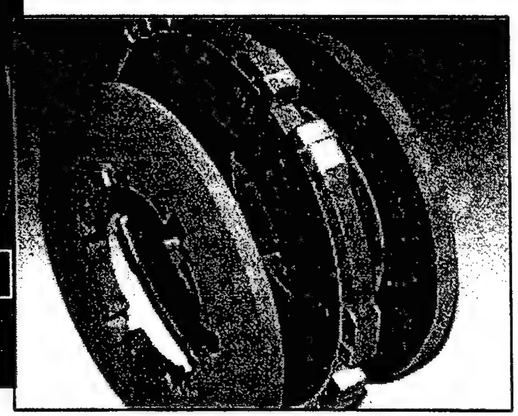
Current Program:
Phase Change Thermal Management

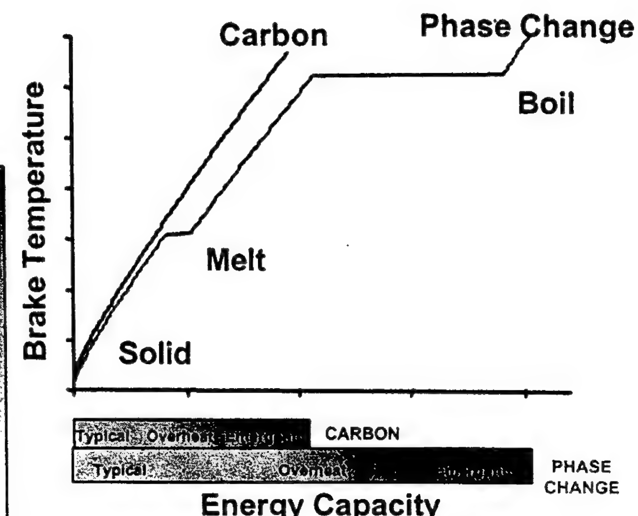
Next Generation Aircraft Brake - Phase Change Brakes (PCB)

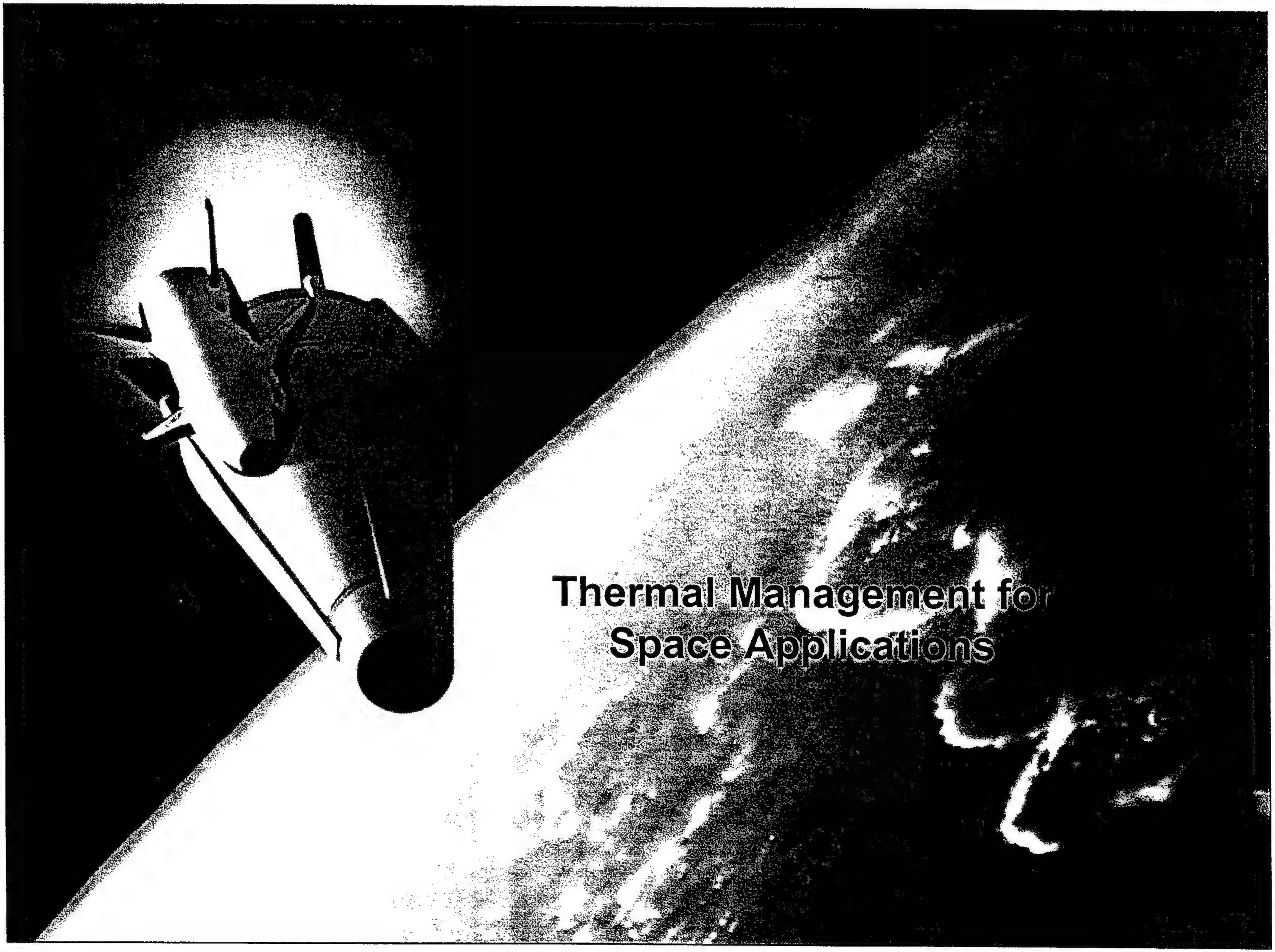
Current operating aircraft brake systems utilize the mass of the brake disks, either steel or carbon/carbon composites, to absorb the heat associated with braking the aircraft. The new concept takes advantage of phase-change (i.e. melting and/or vaporization) of high heat capacity materials to provide at least a

- 30% increased heat absorption capability without increasing weight or volume.
- 30% weight and volume reduction without changing the total heat absorption.

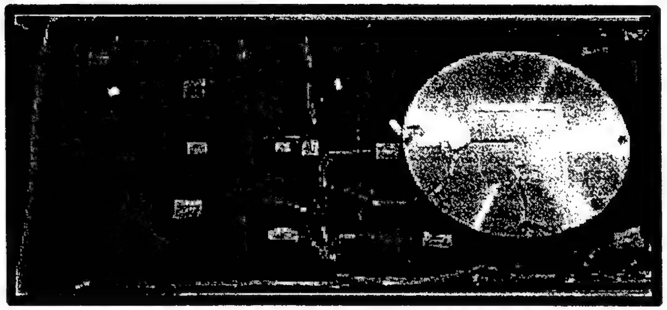






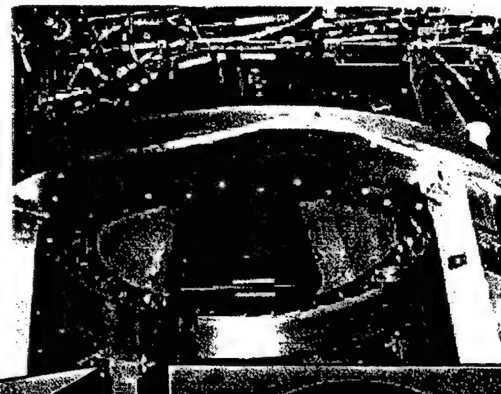

Thermal Management for
Space Applications

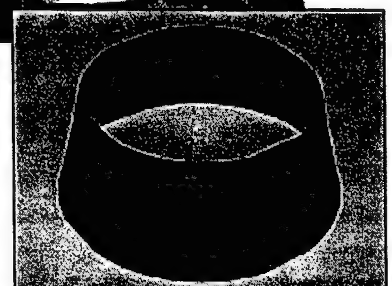
Thermal Management for Space Structures



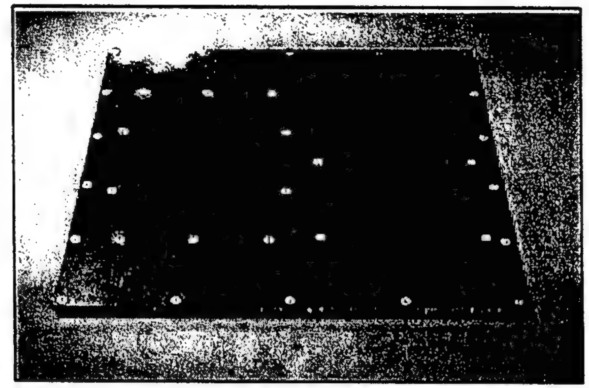
Light Weight Dimensionally Stable Structures

- Demonstrated C-C technology for spacecraft applications
  - Optical bench
  - Thermal doublers
  - Heat sinks
  - Engine shield
- Demonstrated equivalent or better properties than (M55J/K1100)/CE
  - In-Plane thermal conductivity equivalent
  - 3X improvement in through-the-thickness panel conductance
  - Mechanical characteristics equivalent
- Transitioned to
  - MGS
  - Titan's Wideband Instrumentation SubSystem
  - Multifunctional Structure experiment on Deep Space 1 spacecraft





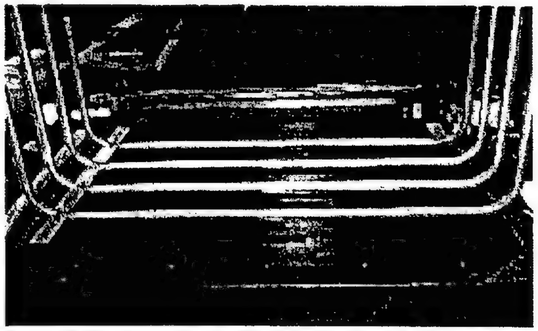
- Low Thermal conductivity
- High strength
- 70% weight savings over current metallic



C-C Spacecraft Radiators Partnership

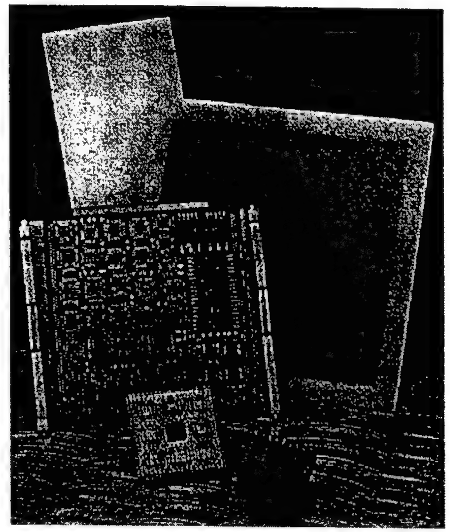
- Low density
  - Decreased launch cost
  - Increased payload
- High thermal conductivity
  - Reduced module temperature
  - Increased module density
- High stiffness
  - Decreased deflections
- Same Thermal Performance as Aluminum radiator with heat pipes
- Flying on Earth Orbiter 1
- Collaborative effort: AF/Navy/NASA/Industry

Thermal Management for Space Structures



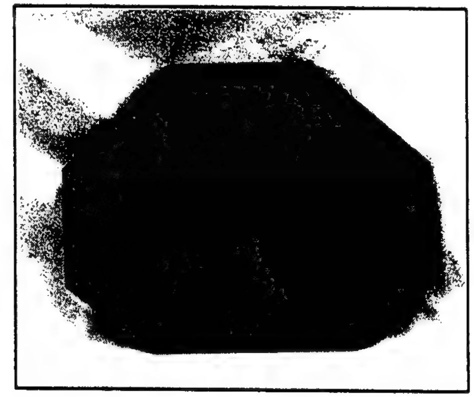
Thermal Structural Materials Solutions for Space

- Reduced Weight
  - Weight savings (~50%)
    - Aluminum: 6 lbs
    - K1100/CE (PMC): 3.3 lbs
- Maintain/improve thermal performance
- Maintain structural performance
- Minimize hardware costs
- Radiator fins flown on STEX spacecraft.
- Battery panel flown on Mars '98 Orbiter.
- Thermal structural panel flown on STRV-1/d.
- Transitioned technology to Stardust



Carbon-Carbon Thermal Planes for Electronics

- 30% lighter weight than Al
- Low thermal expansion
  - Reduced solder fatigue
  - Increased lifetime
- High thermal conductivity
  - Reduced board temperature
  - Increased module density
- High stiffness
  - Reduced board deflections
  - Increased board density



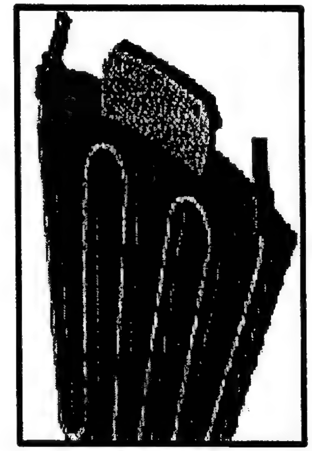
Economical Carbon-Carbon for Spacecraft Thermal Doublers

- High thermal conductivity
  - Reduced module temperature
  - Increased module density
- Low density
  - Decreased launch cost
  - Increased payload
- Low modulus
  - Compliant with surrounding materials

Organic Matrix Composite Heat Pipes

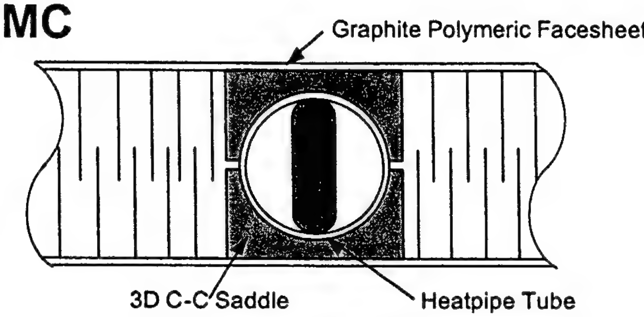
Why OMCs?

- The trend towards OMC structures for weight, stiffness and dimensional stability has driven the need to have composite radiators
- Aluminum heatpipes cannot be readily embedded in composite panels due to CTE mismatch issues
- The use of OMC reduces component weight (i.e. up to 10-20%)
- A CTE compatible heatpipe radiator would allow the incorporation of high thermal conductive materials, resulting in thermal efficient designs.



Technical challenges of OMC heat pipes:

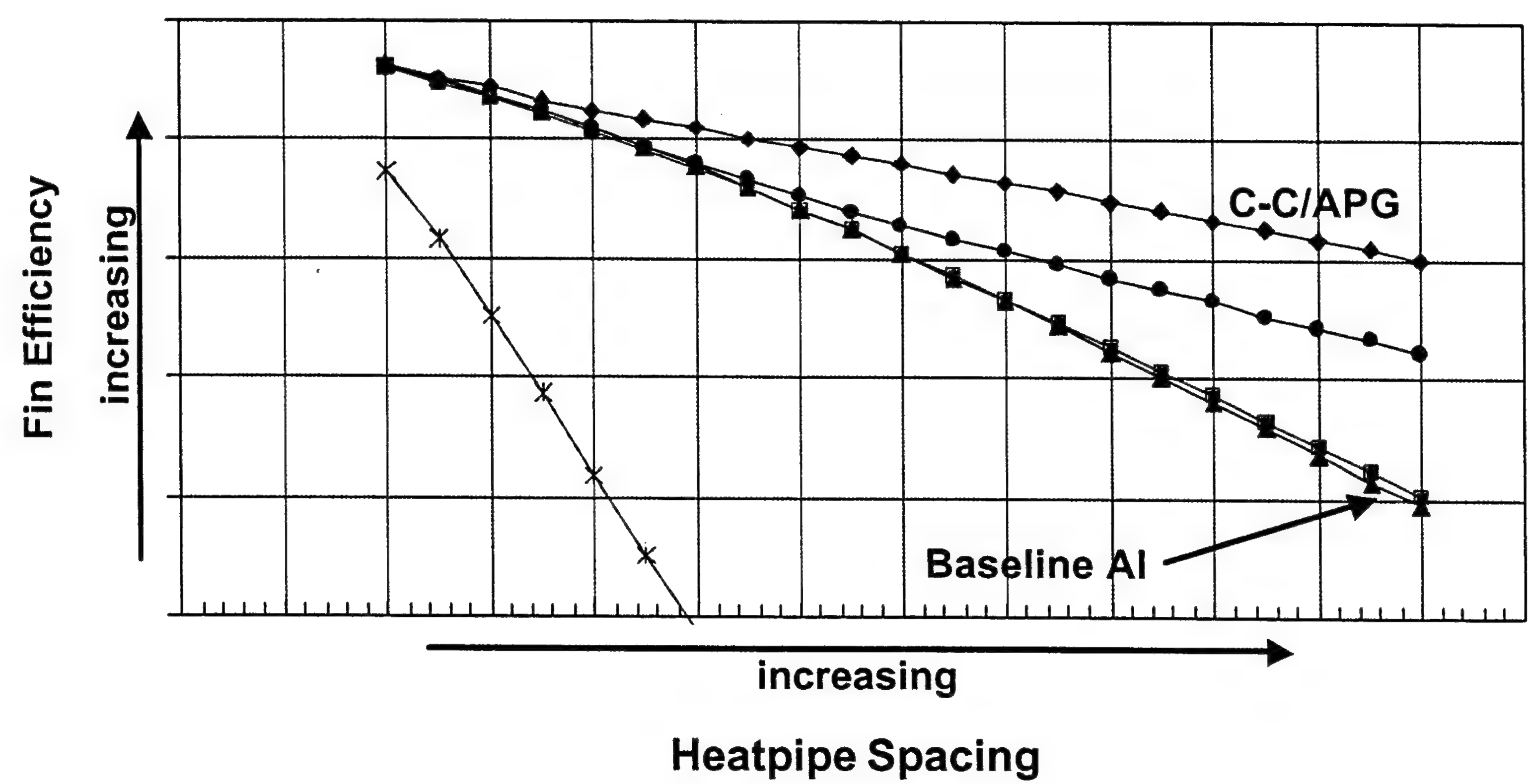
- Non permeable – 2×10^{-10} scc/sec He
- CTE match of hybrid OMC material and interface joint material – ? CTE – 0 to 1 ppm/K
- Integration of thermal efficient heat pipes with OMC skins and honeycomb core components
  - Fewer heat pipes per radiator possible
    - Less weight
    - Less complex design and fabrication processes



Organic Matrix Composite Heat Pipes

OMC Heat Pipes

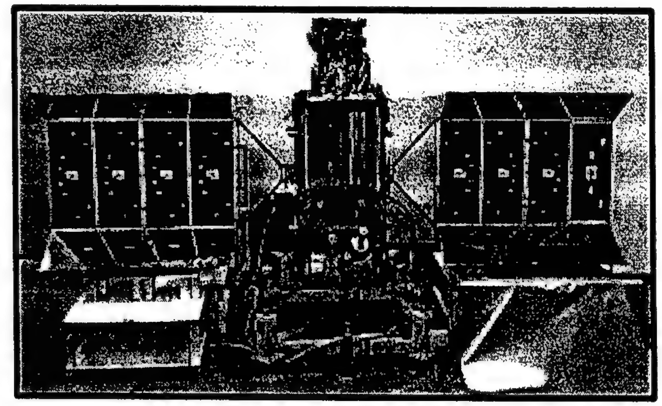
Fin Efficiency versus Heatpipe Spacing



Current Programs: OMC Heat Pipes/Radiators

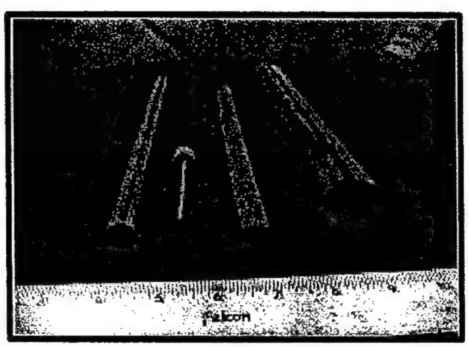
Problem

- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues
- Aluminum radiator panels are incompatible with composite bus structures
- Aluminum doublers add unnecessary weight



Objective

- Develop affordable processing techniques for producing a non-permeable carbon-carbon heat pipes
- Develop techniques to integrate OMC heat pipes into the radiator
- Eliminate Al doublers



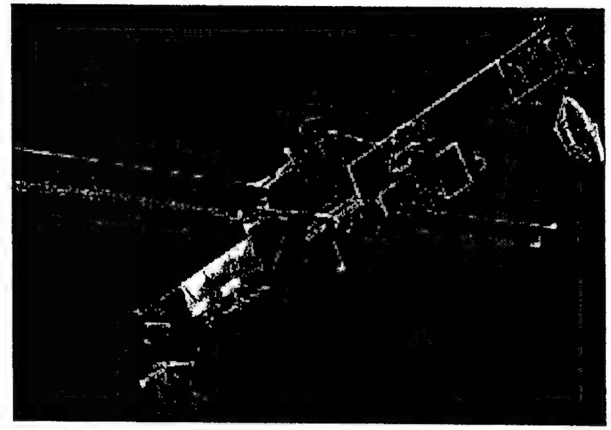
Benefits

- All composite bus
- Lower weight
- Lower fabrication costs
- Greater thermal efficiency

Future Programs: OMC Heat Pipes/Radiators

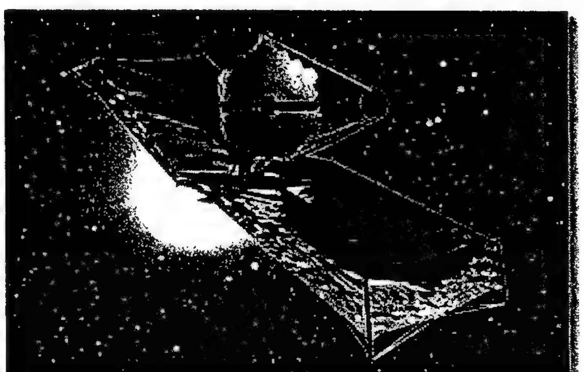
Problem

- Aluminum heat pipes cannot be readily embedded in composite panels due to CTE mismatch issues
- Aluminum radiator panels are incompatible with composite bus structures
- Aluminum doublers add unnecessary weight



Objective/Approach

Next Generation Technologies (??)



Benefits

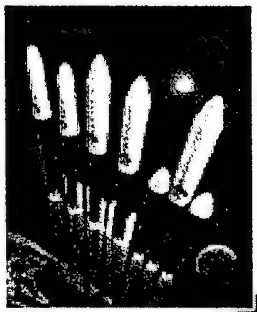
- All composite bus
- Lower weight
- Lower fabrication costs
- Greater thermal efficiency

Beyond current tech

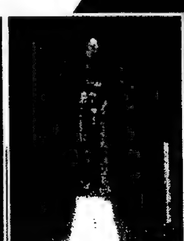
Military Space Plane

AF SOV Gen 2
- Launch-On-Demand: 8 Hrs
- Military Ops Tempo
- Reduce Launch Cost: 100x
- Flexible Launch and Recovery

AF SOV
- Launch-On-Demand: 1 day
- Flexible Payload Options
- Reduce Launch Cost: 10x
- Recall After Launch



AF EELV
- Reduce Launch Cost: 2x
- Launch-On-Schedule
- Reconfigure Vehicle For Payload
- No Recall After Launch



Attributes:
- Responsive and Affordable Delivery of Mission Assets To, Through and From Low Earth Orbit
- Multi-Mission Capable With Inter-changeable Payloads
- Rapid Turn Time and Alert Hold Capability
- Launch and Recovery from U.S. Bases
- Nearly All Weather Operations
- Autonomous Operation Design
- Primary Structure: 500 sorties (overhaul @ 250)
- Engine Life: 250 sorties (overhaul @ 100)
- Remove & replace main engine: 4 hrs
- Maintenance man hours per sortie: 50

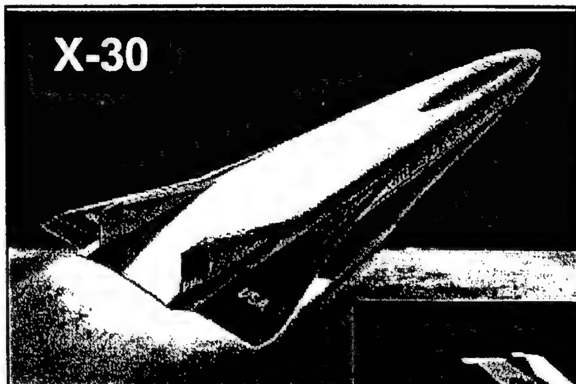
BASELINE
Shuttle / ELVs

Near Term — 2000 – 2008

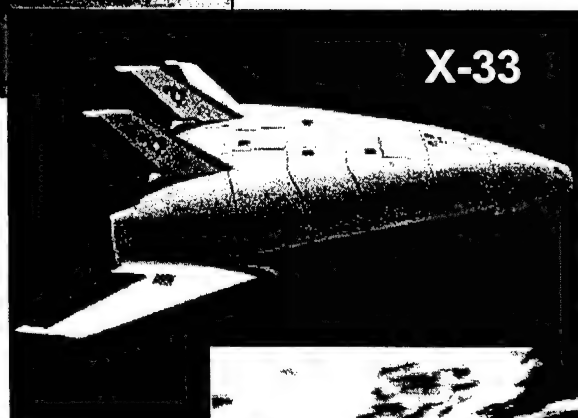
Mid Term

Far Term — 2016 – 2025

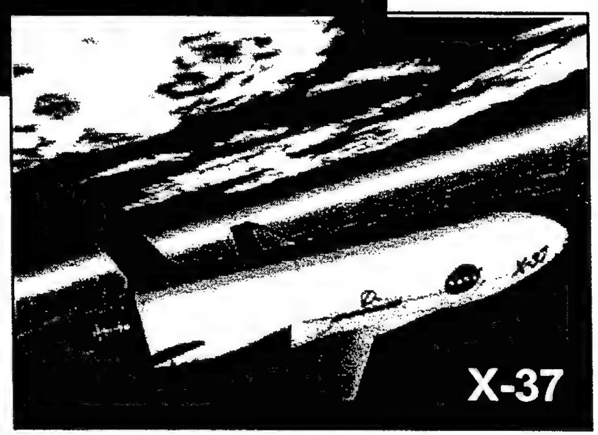
X-Vehicles LE TPS



- TPS (<1500) – Titanium Matrix Composite
- TPS (1500-3000F) – C-C and C-C/SiC
- TPS (>3000) – Active Cooling (C/SiC and C-C w/MoRe heatpipes, heat exchangers)

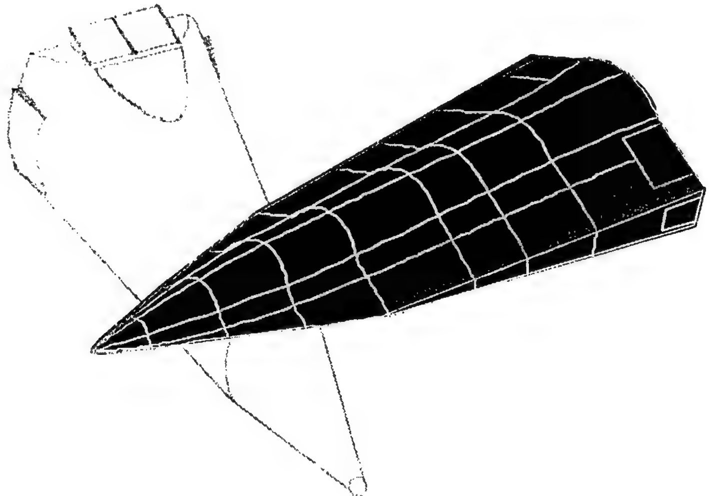


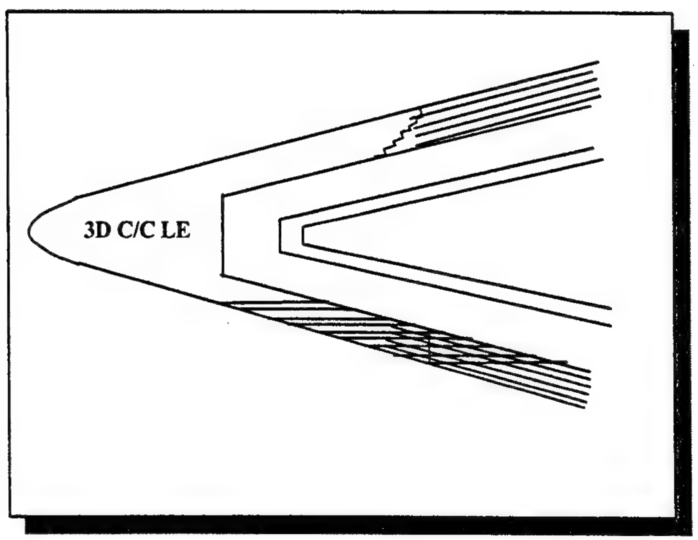
- Nose Cap – C-C
- Leading Edges – C-C
- Other – metals, tiles, blankets,



- Nose Cap – TUFI/AETB tiles
- Leading Edges – TUFI/AETB tiles

Current Programs: Thermal Protection Materials





OBJECTIVE

- Develop low cost, advanced TPM for the CAV (Common Aero Vehicle)

APPROACH

- Modified CC aeroshell: thermally efficient, structural, low cost
- Insulation layer: lightweight, thin section
- Integral stackup: aeroshell + insulation + structure
- Triaxial braiding: thin wall CC aeroshell
- Leading edge to heatshield transitions
- Cold wall ablator (CWA) overlay: low CC aeroshell recession
- Integrated CC leading edge: high bending resistance
- Modified CC processing: cost reduction

BENEFITS

- Thermal efficiency = minimal areal weight & thickness
- Mechanical properties degradation ? 15% of allowables
- Cost reduction over current material systems of 45%

CUSTOMERS

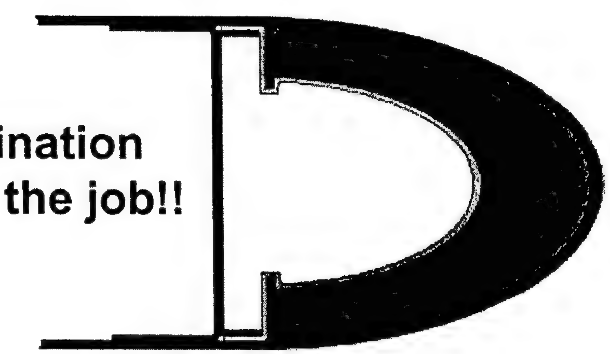
- CAV; SOV/SMV/Launch Vehicle technology transfers

Next Generation Leading Edge TPS Concept

Rainbow Solution

- "Think out of the Box" design philosophy
- Thermal management solution for thermal protection
- A hybrid concept
- Structurally integrated approach – not parasitic
- Novel combination of materials
  - C-C
  - Ceramics
  - Metals
  - Foams
  - Aerogels
  - Phase Change Materials

The right combination of materials for the job!!



- Focus is on
  - Reliability/Durability/Supportability
  - Cost/Manufacturability
- One ongoing effort with Boeing, and one SBIR to be awarded on Jan 2003

Thermal Management Summary

AFRL/ML actively engaged in thermal management research and transition

- Identified the area as a key technology solution to address Air Force needs
  - Successful technology transitions demonstrated
- Integrated well with other organizations
- Broad spectrum of R&D programs and applications
- Excellent potential for transition (military & commercial)
  - Working closely with DoD, customers and industry
  - Focus is on near and mid-term applications
  - Future Work:
    - Nanomaterials for enhanced multifunctionality
      - Dimensional control, performance enhancement
    - Carbon Foam applications: heat exchangers and radiator panels
    - Novel thermal protection applications

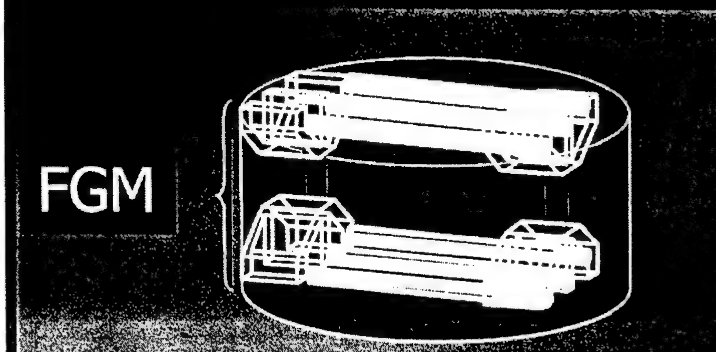
FABRICATION TECHNIQUES FOR MAKING AN EFFICIENT MICRO-HEAT EXCHANGER

P. Kwon
Department of Mechanical Engineering
Michigan State University
East Lansing, Michigan

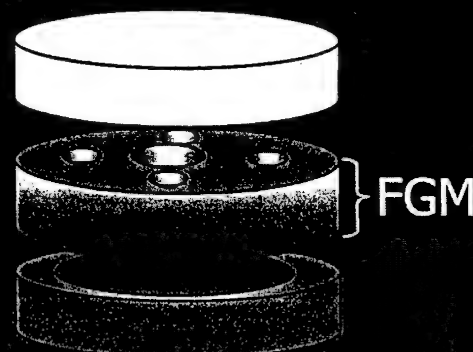
Methods to remove heat

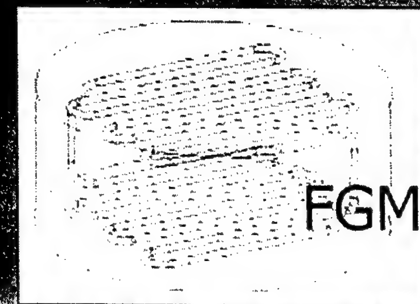
- Heat spreaders
  - One of the most common methods
  - Dissipates heat to the environment by forcing air through pin arrays or fins or cooling naturally.
  - Materials with high thermal conductivities and heat capacities. (diamond, silicon nitride, molybdenum etc.)
- Cooling fluids circulating in closed channels
  - "Microchannels" (100 to 300 microns in diameter)
  - Stringent requirements
  - Miniaturization
  - Fluids – One-phase and Two-phase System

Possible Designs

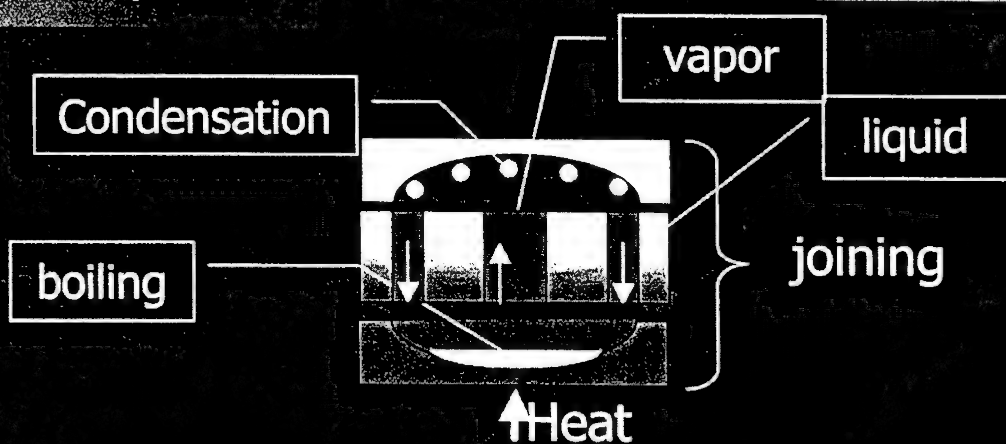


One-phase System





One-phase System

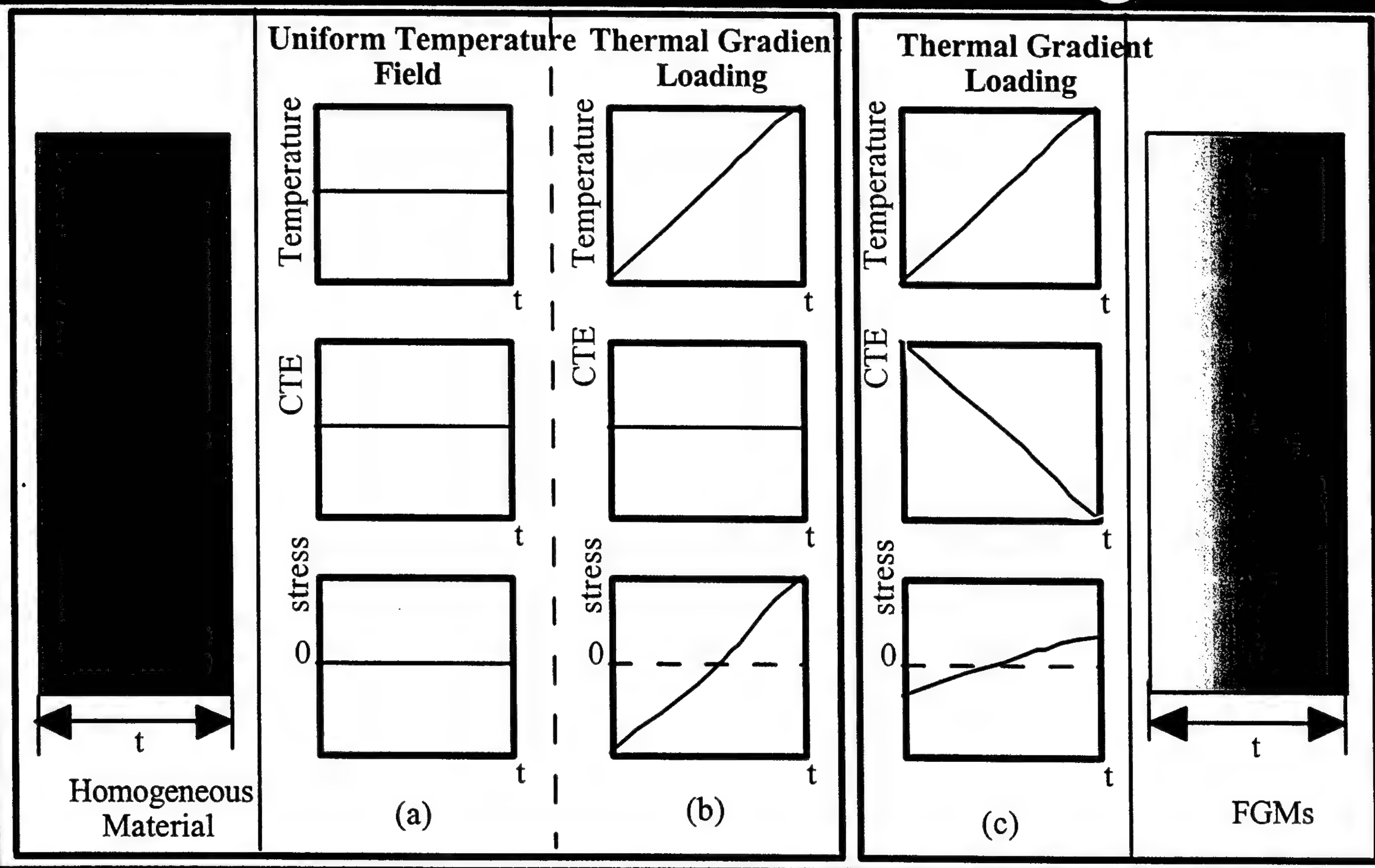


Two-phase System

OBJECTIVES

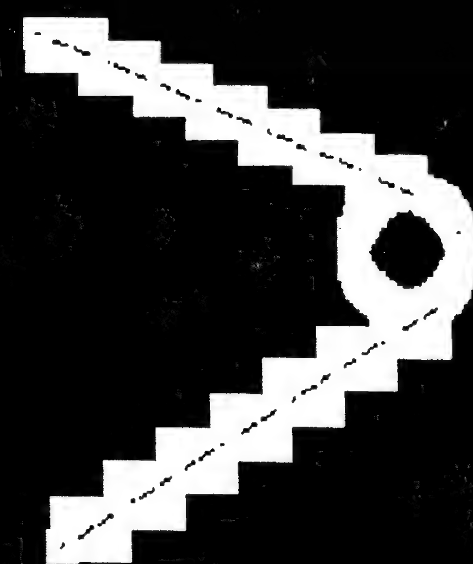
- Multifunctional – Structure + Thermal Mangement
- Processing Issues
  - Functionally Gradient Medium (FGM) with minimum residual stress
  - Introduction of channels and
  - Joining techniques
- Process in general
  - More Flexible: Powder Processing
  - More Complex: Process techniques & model
- Applications: Electronic Cooling, Cutting Tool, Turbine Engine etc.

Micromechanical Design



Effective Properties

- "Homogeneous" Materials
- **Fiber Composites:**
  - Rule and Inverse Rule of Mixture
- **Particulate Composites:**
  - **Single Ellipsoidal Inclusion** [Eshelby; 1957, 1961,1962]
  - **Many Ellipsoidal Inclusions**
    MT [Mori & Tanaka; 1973],
    GSC [Christensen & Lo; 1979], DS [Norris; 1985] & Many Others



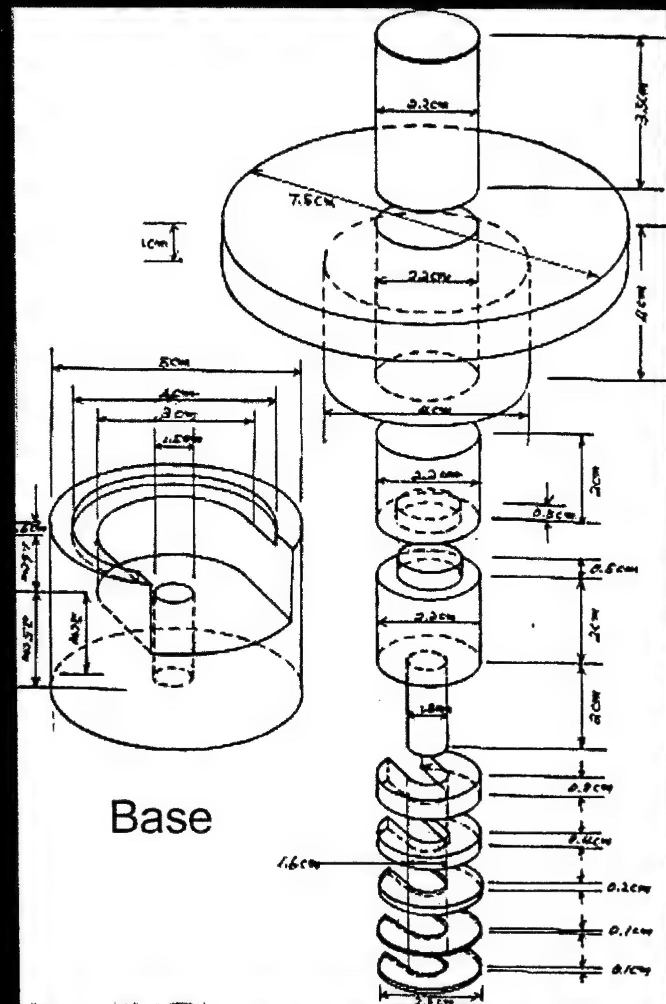
Eshelby's Problem

Mori-Tanaka Model

Fabrication Techniques

- Micro-texturing
  - Multi-layers – Each layer of macroscopically homogeneous mixed powders
- Micro-configuring
  - Internal Geometry - Fugitive phase
  - Surface Geometry – Fugitive phase & Machining partially sintered ceramics
- Joining Techniques
  - Fully Sintered Ceramics (FSC)
  - Partially Sintered Ceramics (PSC)
  - Compacted Ceramic Powder (CCP)

Multilayer Powder Compaction

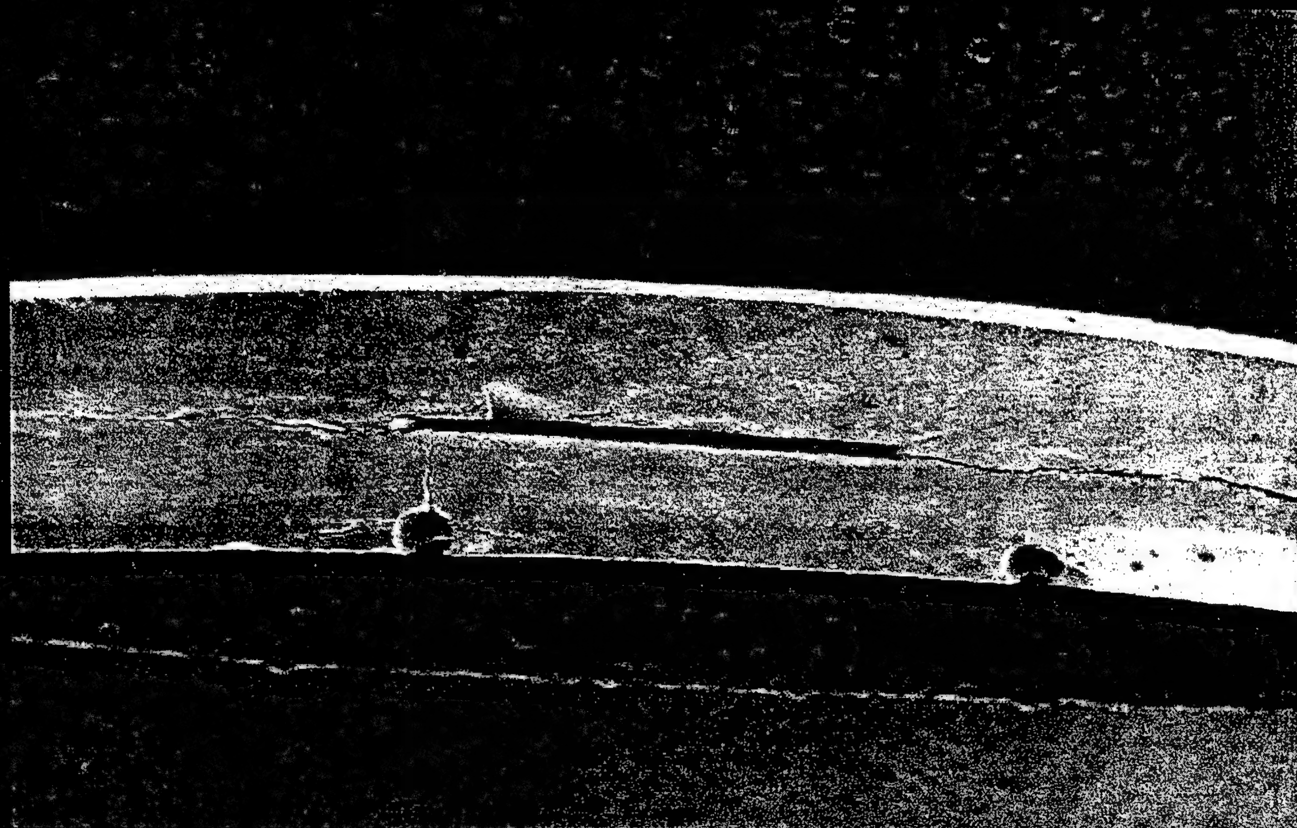


Die Cavity

Bottom
Contact
Dies

Spacer

Residual Stress Effect on FGM



Alumina

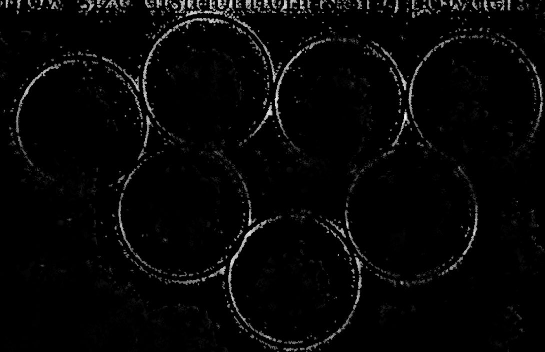
Zirconia

Approach

- Develop a powder processing protocol
  - Minimize process-induced residual stress in FGMs
  - The intertwined functionality existing among powder characteristics, processing conditions and corresponding shrinkage and densification behaviors.
- Plans to develop Process Model
  - Development of Compaction Model
    - Yield Surface
    - Flow rule
  - Development of Sintering Model

Powder Characteristics

Narrow size distribution(NSD) powders

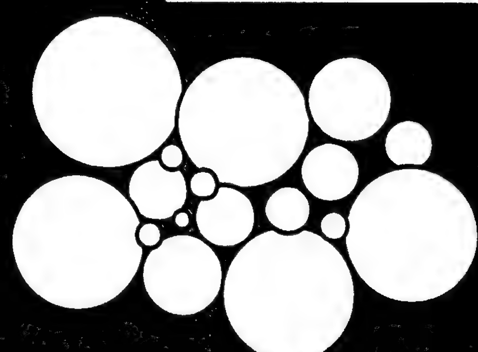


High Shrinkage

low CTE material

high CTE material

Bi-material

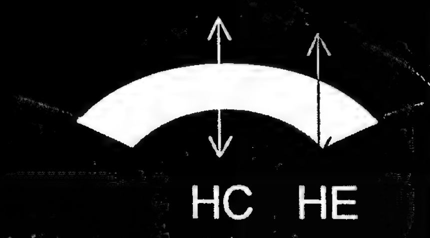


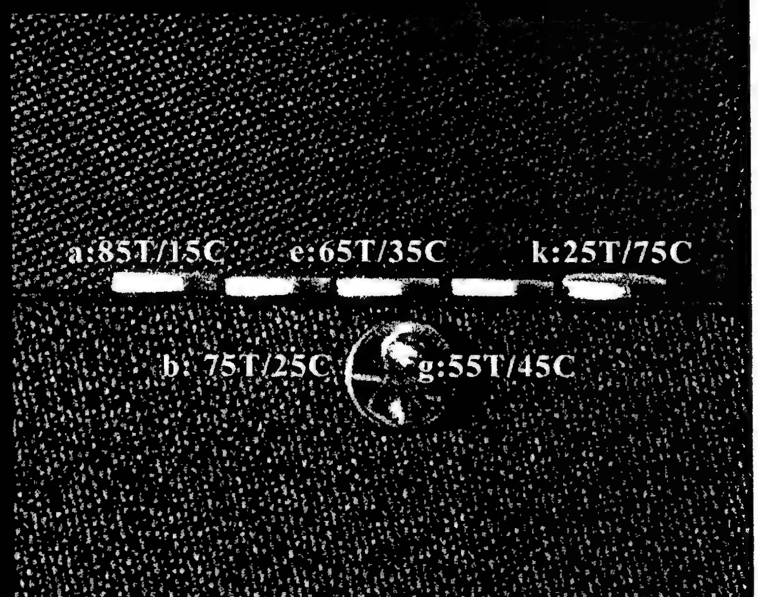
Low Shrinkage

Controlling Residual Stress

TMDAR

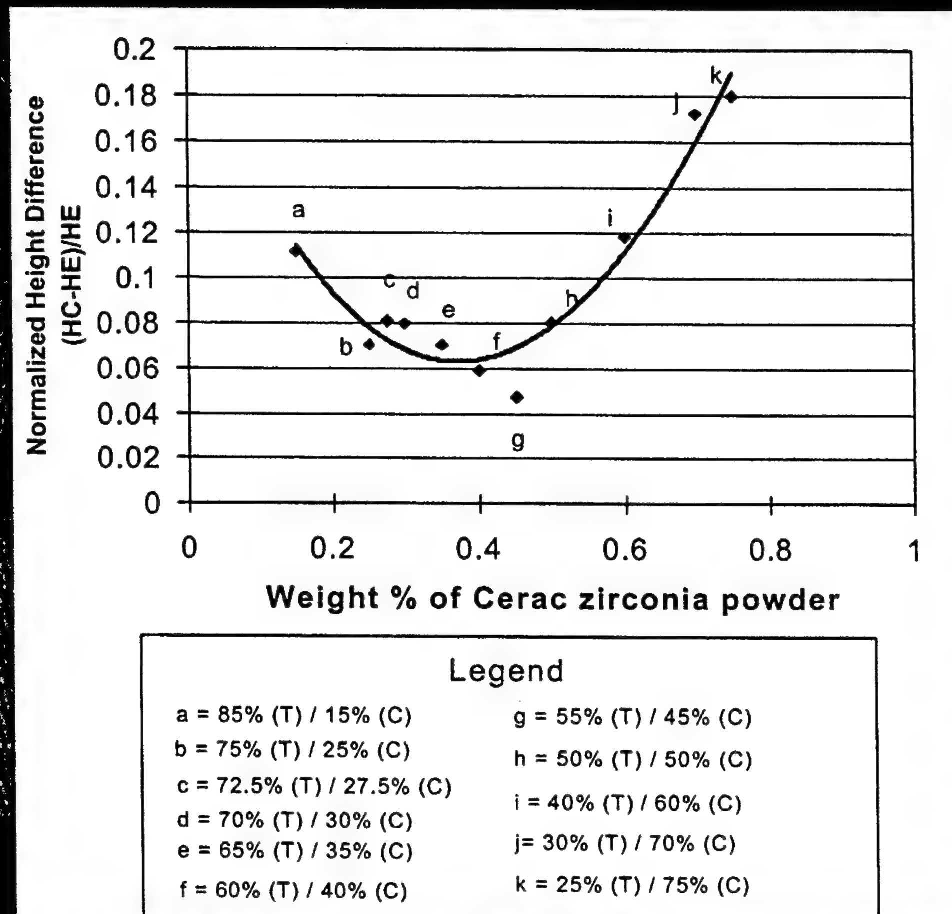
Tosho/Cerac





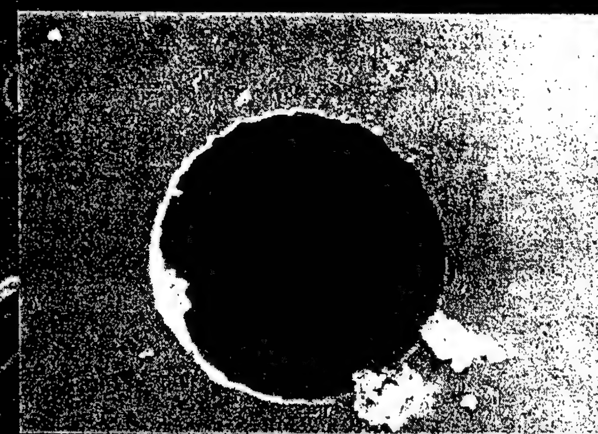
T

C

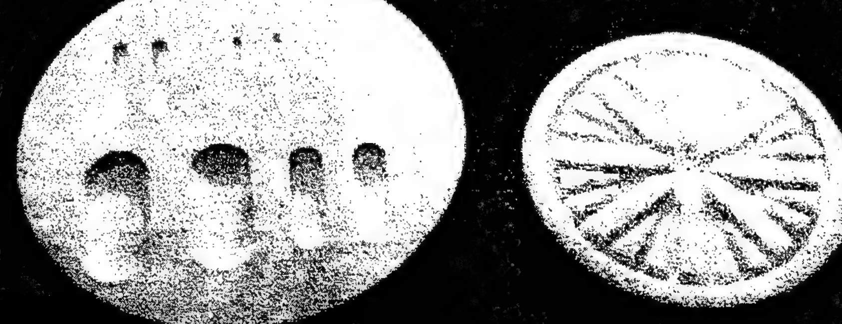


Internal & External Channels

CNC-Machined on PSC, Sinter & Join



CNC-Machined on PSC, Sinter & Join



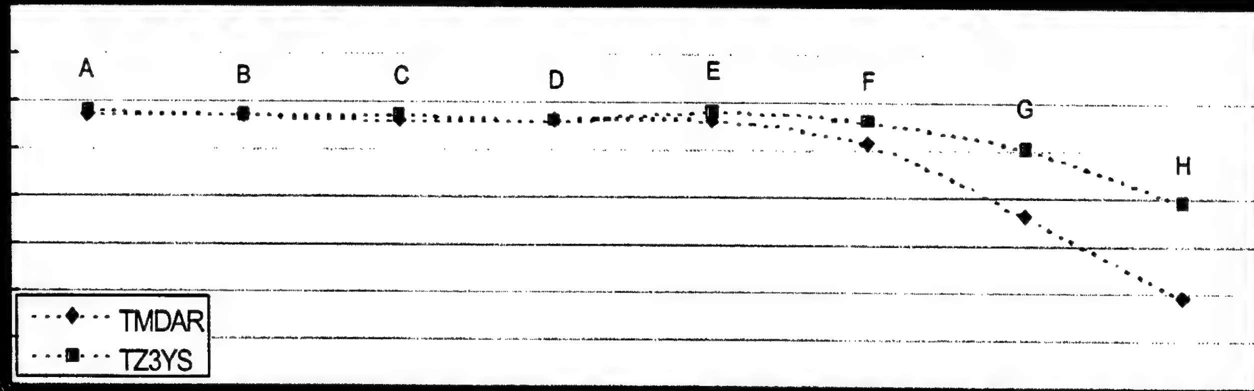
Fugitive Phases: Various Polymers & Graphite

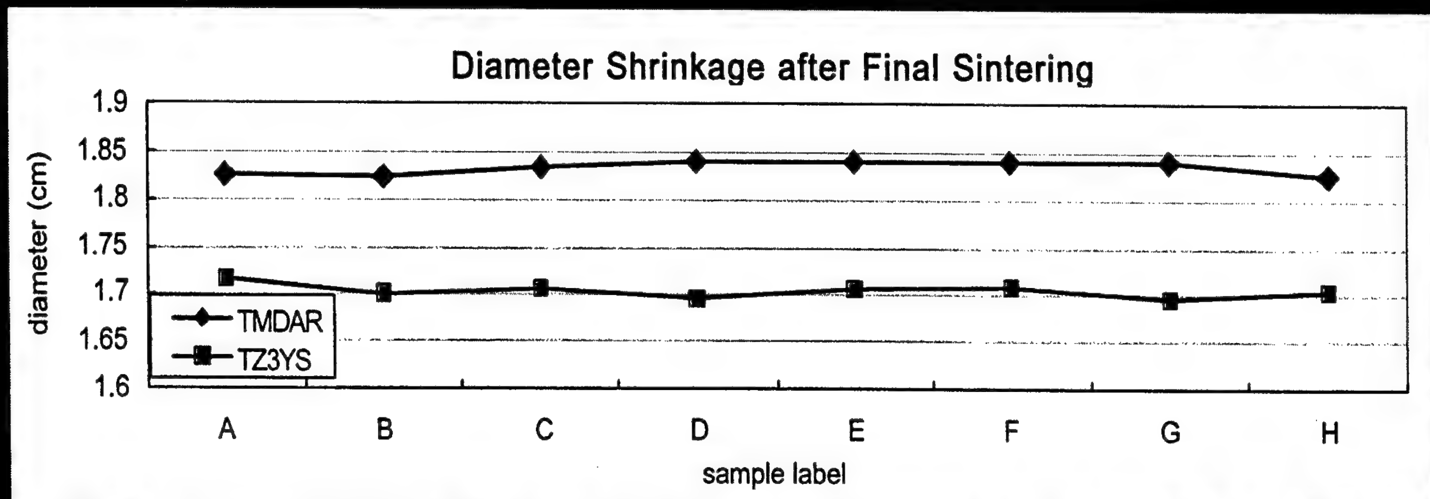
Powders Used

Materials	Manufacturer	Powder Name	Average Particle Size (micron)
Alumina	Tamai	TMDAR	0.2
FSZ	Tosoh	TZ-8YS	0.58
PSZ	Tosoh	TZ-3YS	0.6
	CERAC		1.23
	Sumitomo	OZC-3YC	0.9

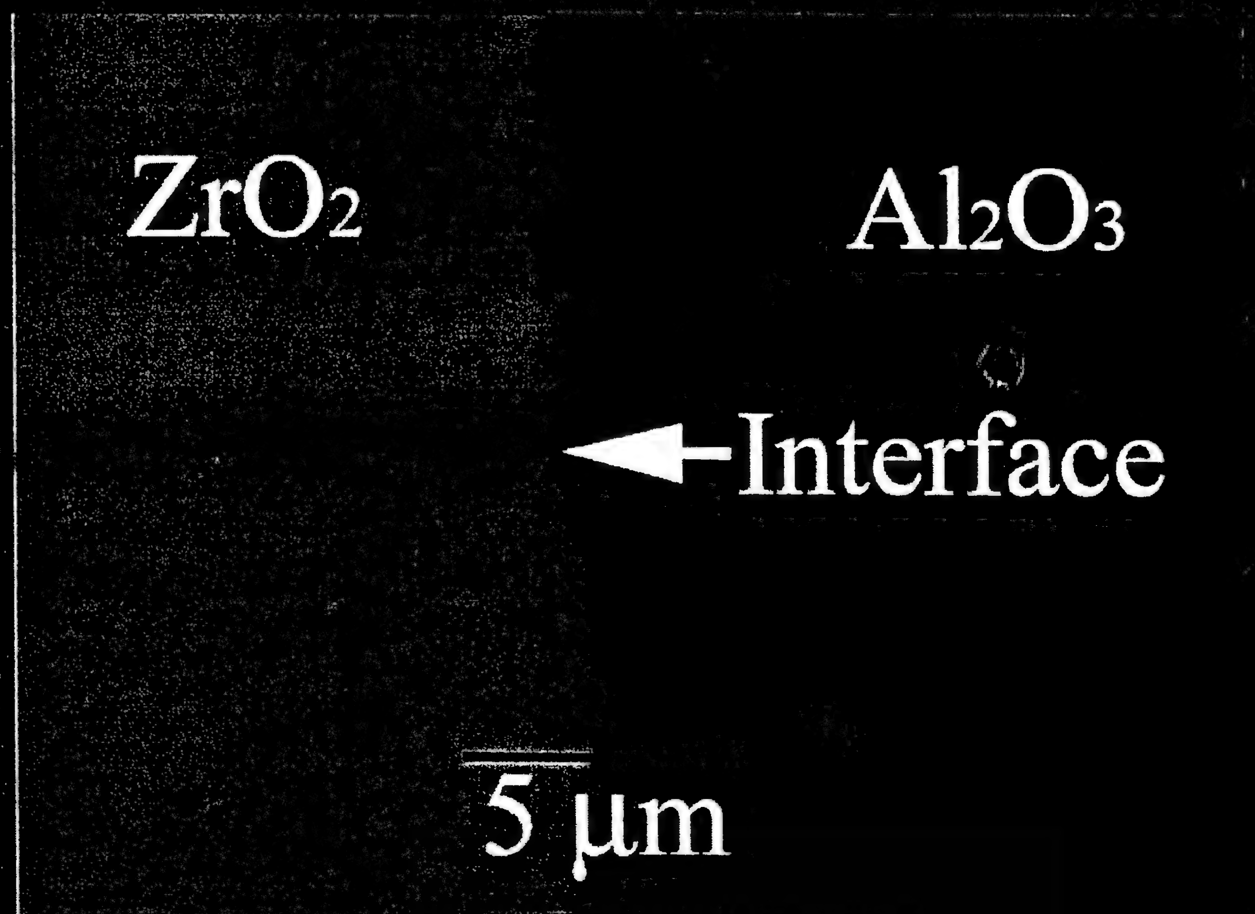
Dimensional Changes

Diameter Shrinkage after Pre-Sintering

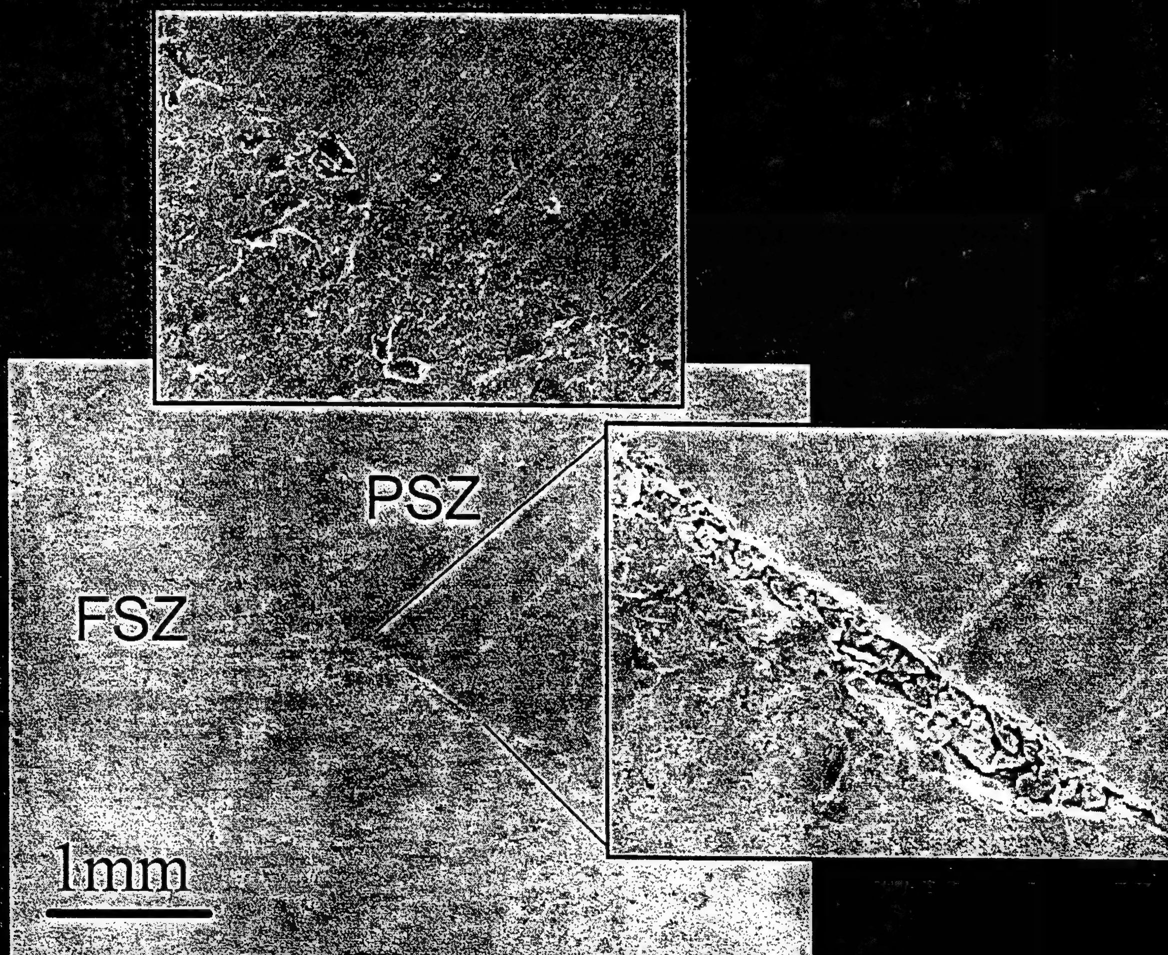




Joining with Silica film



Joining without Silica Film



Summary of Processing

Internal Channels

- Powder Mixing
- Compaction
  - Fugitive Phase
- Pre-sintering (1000°C for 3hrs)
- Sintering
- Polishing and Spin-coating
- Joining

Surface Channels

- Powder Mixing
- Compaction
- Pre-sintering (1000°C for 3hrs)
- CNC-Machining
- Sintering
- Polishing and Spin-coating
- Joining

3-D WOVEN COMPOSITE STRUCTURES WITH INTEGRATED FIBER OPTIC SENSORS

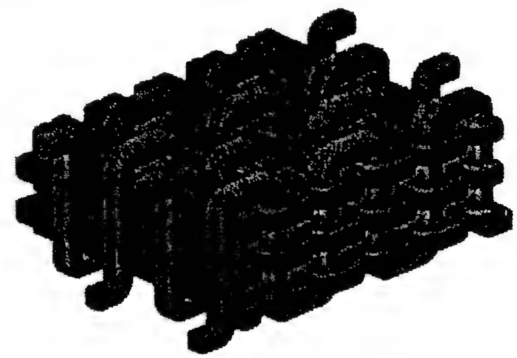
Dr. Alexander Bogdanovich
Vice President, Research & Development
3TEX, Inc.
109 MacKenan Drive, Cary, NC 27511
Phone: 919-481-2500 ext. 113
E-mail: bogdanovicha@3tex.com

Presented at the 1st Air Force Workshop on "Multifunctional Aerospace Materials"
October 23-23, 2002, Purdue University, W. Lafayette, IN

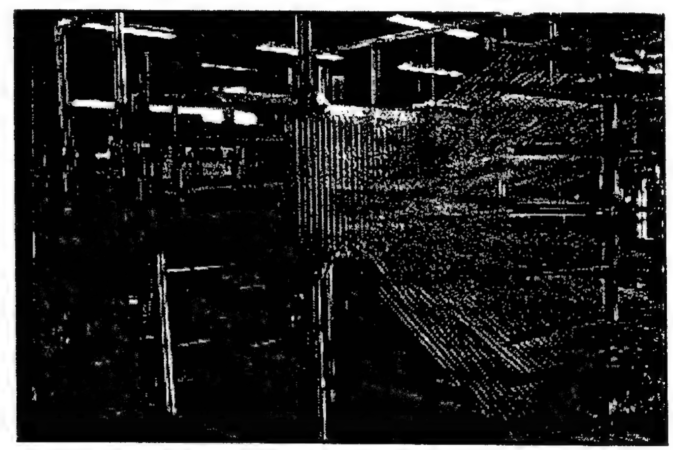
3TEX

IN SITU EVALUATION OF 3-D WOVEN COMPOSITE STRUCTURAL PERFORMANCE USING FIBER OPTIC SENSORS
AFOSR STTR PHASE I and PHASE II (to start in November 2002)
Awarded to 3TEX, Inc.

- <u>The concept of this novel technology:</u>
  To use three orthogonal reinforcement elements (yarns placed in warp, weft and Z directions) of a 3-D woven fabric preform as natural carriers of integrated optical fibers and sensor systems associated with them.
- <u>Objective</u>:
  In-situ strain monitoring of composite structures at any location within the structure and in any of the three orthogonal directions by means of fiber optic sensor systems integrated in the 3-D reinforcement elements.
- <u>Concept validation</u>:
  Use of automated 3-D weaving machines for manufacturing fabric preforms and VARTM composite processing technology for producing composite panels and bonded joints with integrated EFPI sensors in all three directions.



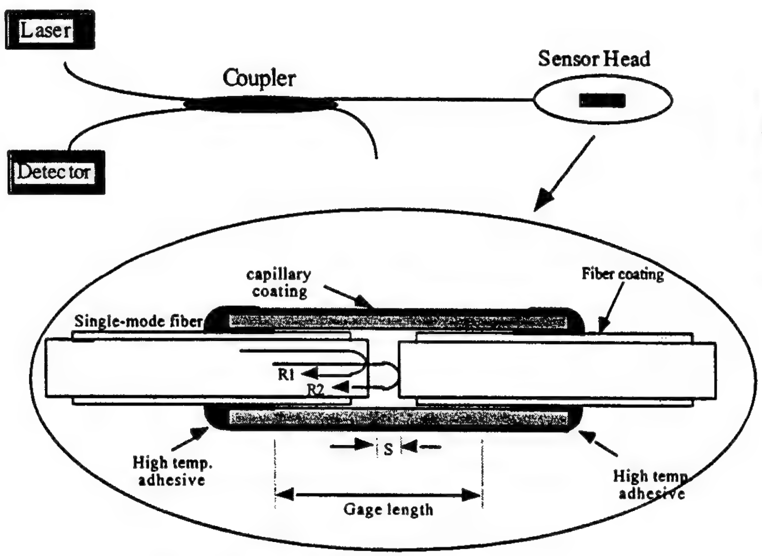
Schematic of 3-D orthogonal woven preform

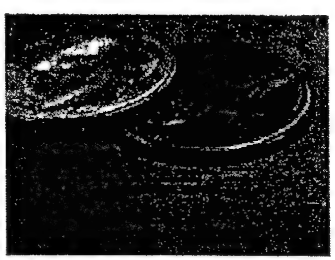


Industrial 3-D weaving machine (3TEX)

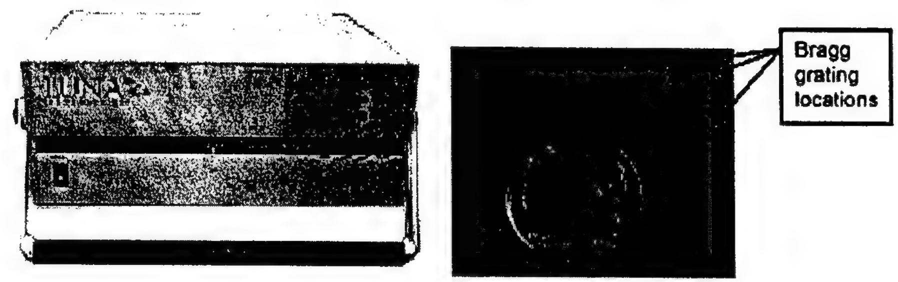
SENSOR SYSTEMS FOR SPECIFIC IMPLEMENTATIONS AVAILABLE FROM LUNA INNOVATIONS

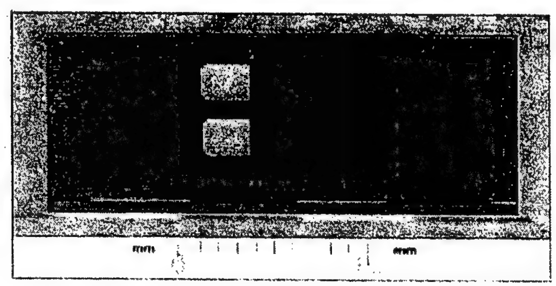
Extrinsic Fabry-Perrot Sensor System

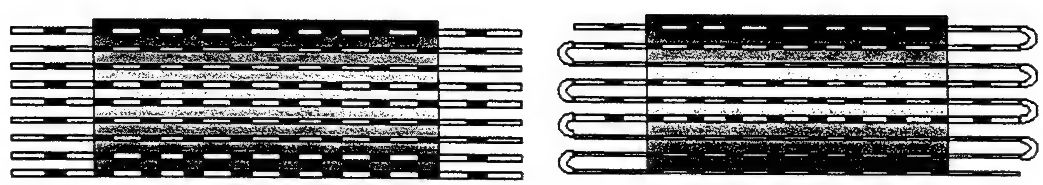




Bragg Grating Distributed Sensing System

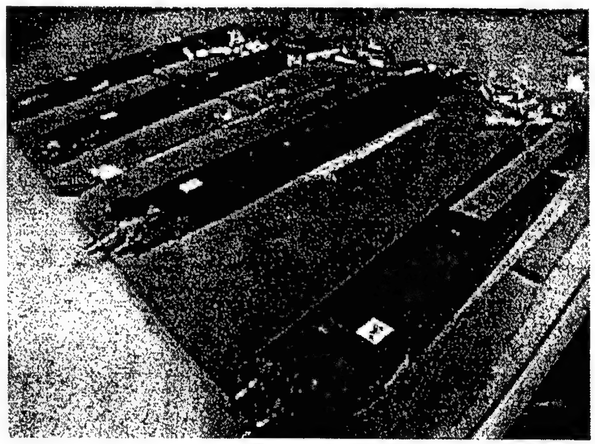




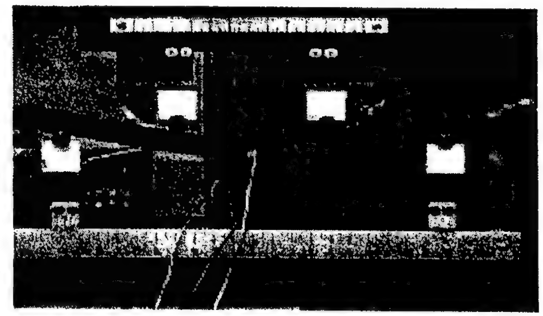


EFPI SENSOR INSTRUMENTED CARBON/EPOXY SPECIMENS USED FOR THE CONCEPT VALIDATION

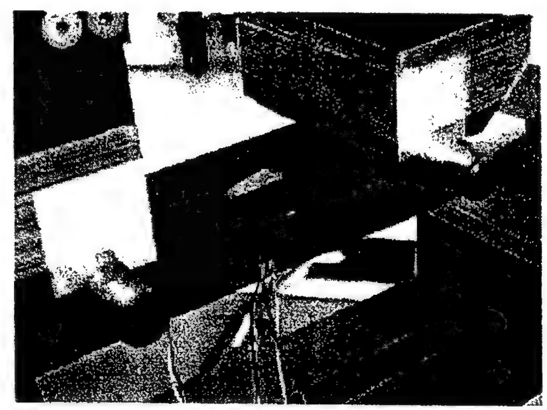
Instrumented 3-D weave flexure specimens



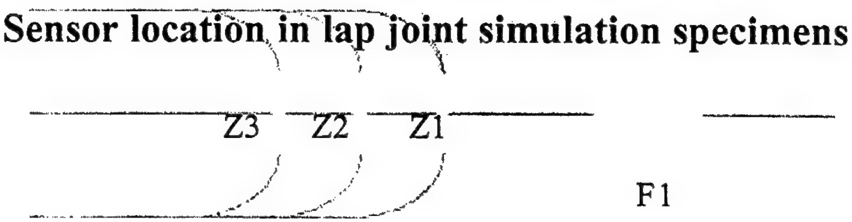
4-point bending test of beam specimen



4-point bending test of beam with drilled hole

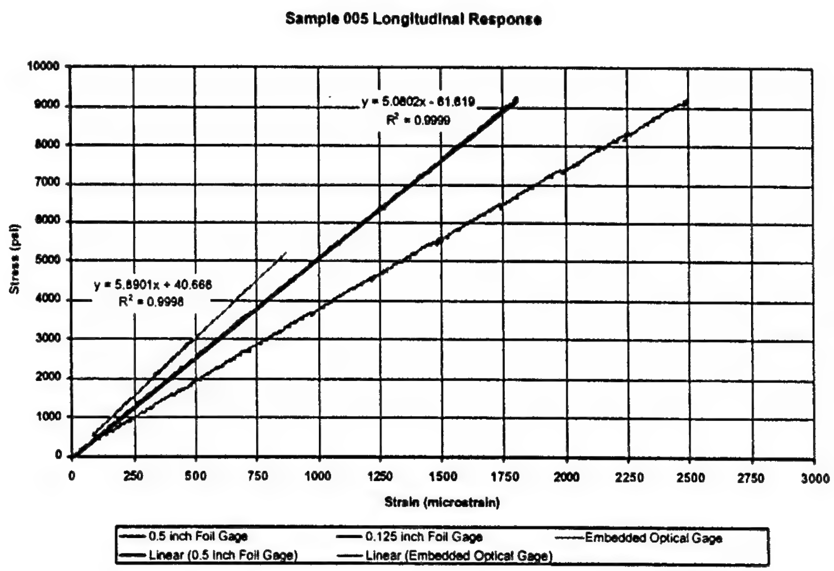


Sensor location in lap joint simulation specimens



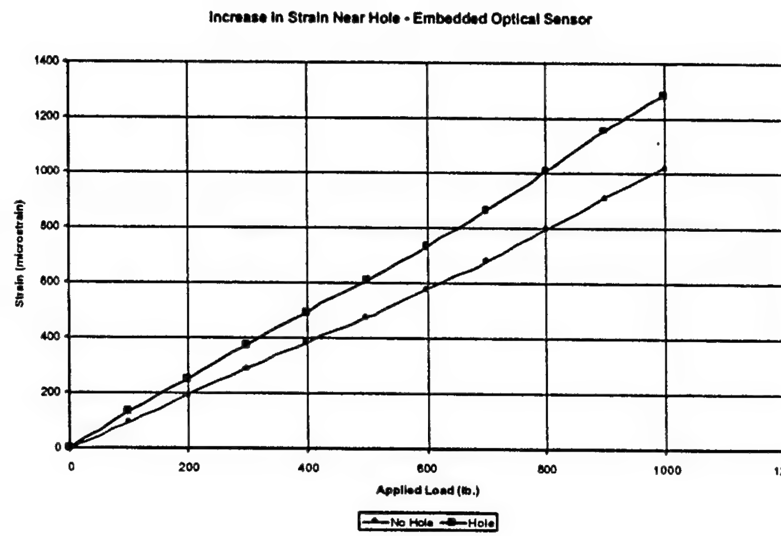
SOME RESULTS OF THE CONCEPT VALIDATION

4-point flexure test longitudinal strain data from EFPI sensor and foil gages



A smaller foil gage shows strain (-----) more characteristic for a resin pocket.
A larger strain gage (-----) covers resin pocket and some of the yarn area next to the specimen surface.
The EFPI sensor shows strain (-----) within yarn adjacent to the specimen surface.

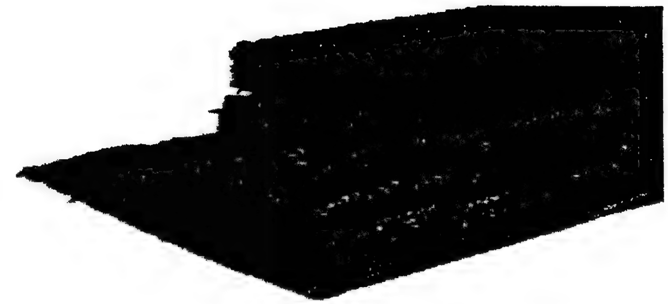
Strain concentration near hole captured by EFPI sensors in 4-point flexure test

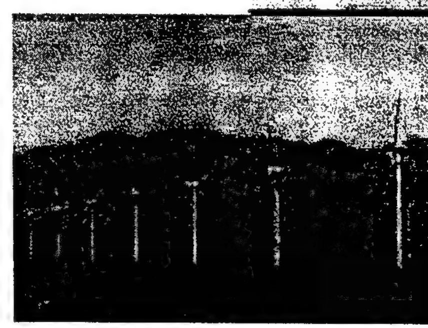


A through-thickness hole was drilled near integrated EFPI longitudinal strain sensor.
Strain recorded by the sensor in the presence of hole (-----) is significantly higher than the strain at the same location in the absence of hole (-----).

ANTICIPATED BENEFITS FOR DESIGN AND APPLICATIONS

- Embedding fiber optic sensors into 3-D weave composites in the zones of anticipated high stress/strain gradients and simulating in-service loading conditions will provide invaluable information for
  - **optimizing 3-D fiber architecture in the preform for each specific type of loading conditions**
  - **selecting most suitable fiber and resin combinations for composite structures**
  - **optimizing thickness and other geometric parameters of the structure**
  - **combining experimental and theoretical tools for structural analysis and design**
  - **significantly increasing reliability of design, thus reducing cost of inspection, repair and maintenance.**





BLUE ROAD RESEARCH

In-Situ Evaluation of Composite Structural Performance in Presence of High Stress/Strain Gradients Using Multi-axis Fiber Grating Strain Sensors

Eric Udd

Stephen Kreger

376 NE 219th Avenue

Gresham, Oregon 97030

503-667-7772 (P)

503-667-7880 (F)

www.bluerr.com

Strain Measurement Interior to Composite Parts-Background/Partnerships

- First quantitative measurements of multi-dimensional strain interior to composite parts
- Blue Road Research partnered with U of DL, interest from Boeing (aircraft, spacecraft) and Thiokol (rocket motors)
- Synergistic with funded research from NASA (multi-axis strain measurement), health monitoring for composite cryo tanks and rocket motors (AFRL/WPAFB and AFRL/Edwards AFB)

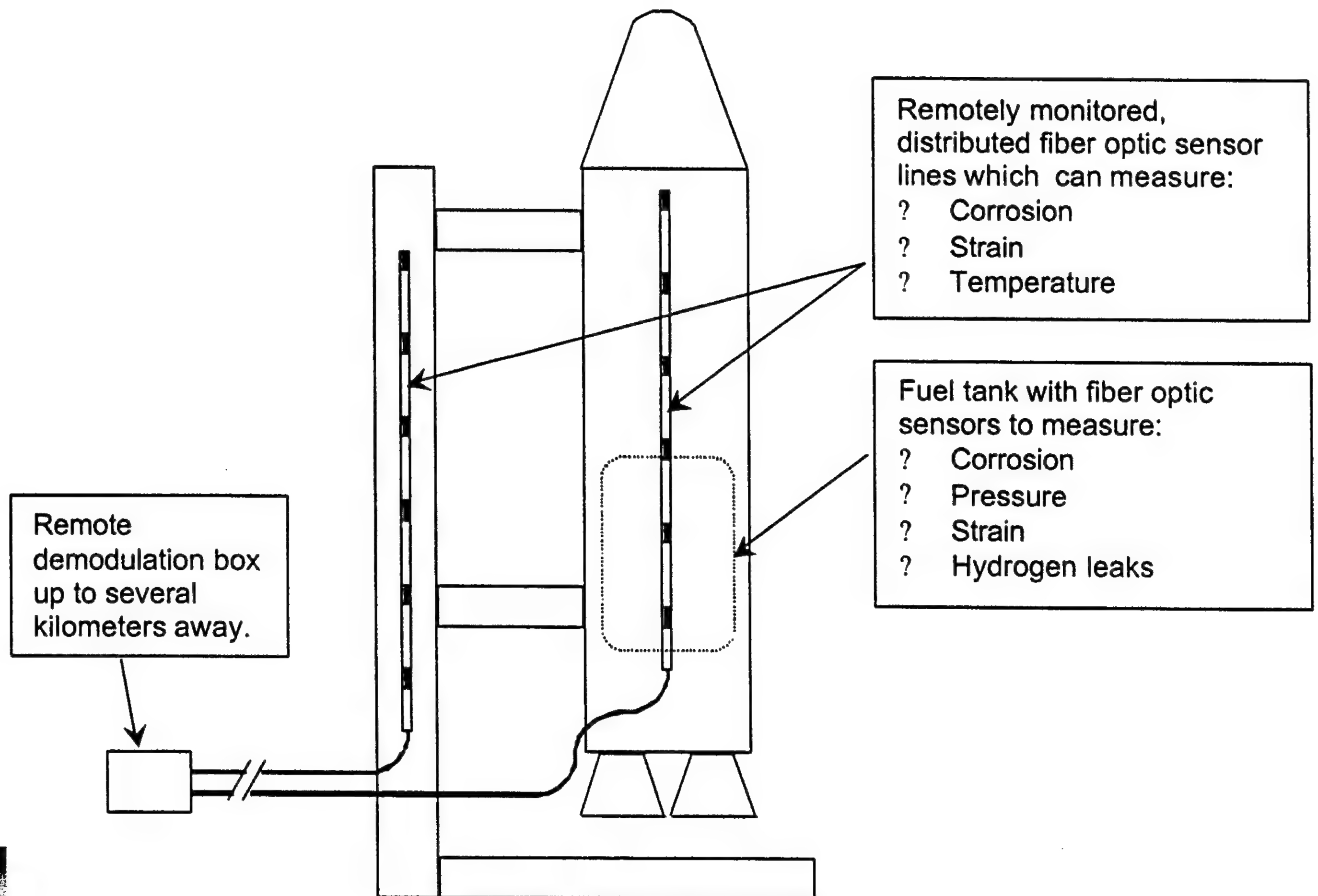
BLUE ROAD RESEARCH

Strain Measurement Interior to Composite Parts- Relevancy

- Multi-dimensional strain measurement using fiber gratings interior to complex composite parts
- Electrical alternatives are bulky and not compatible with conductive materials
- Embed multi-axis fiber grating and obtain quantitative measurements of transverse strain and strain gradients
- Applies to aircraft and launch vehicle composite parts

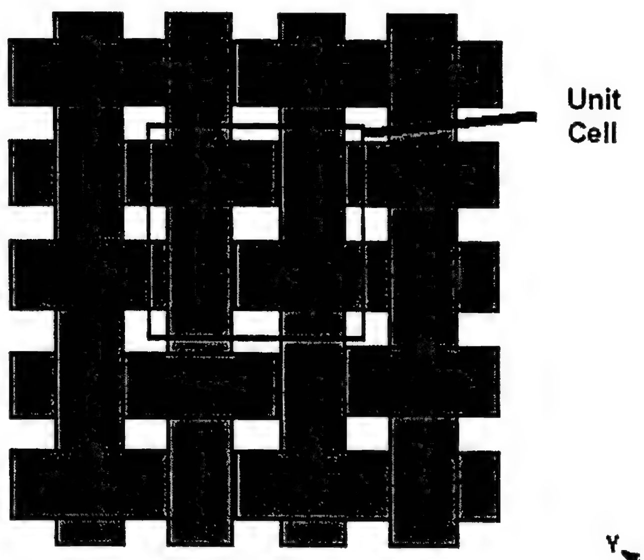
BLUE ROAD RESEARCH

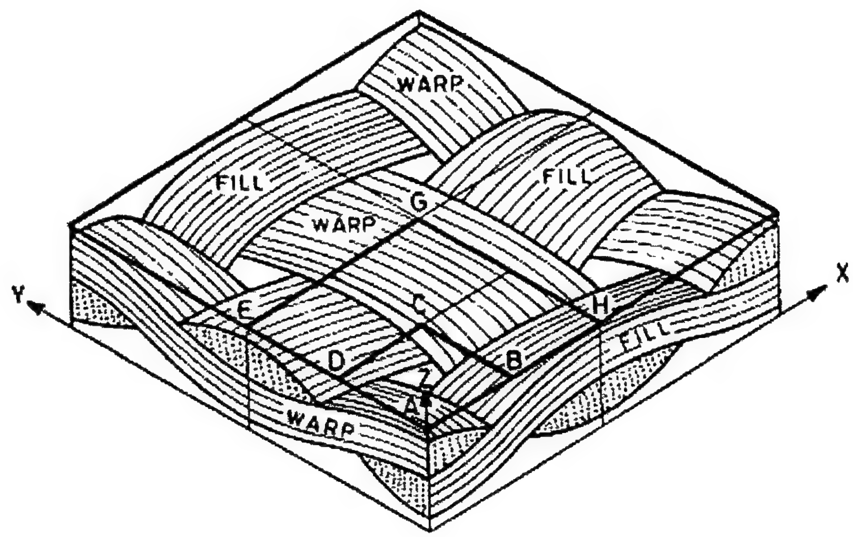
Distributed Sensors in Space Vehicles



BLUE ROAD RESEARCH

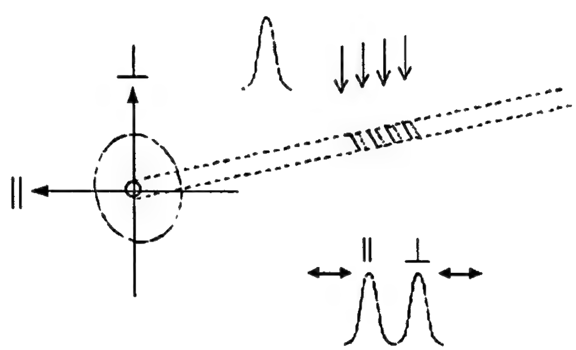
Schematic of the Microstructure and Unit Cell of Plain Weave Fabrics

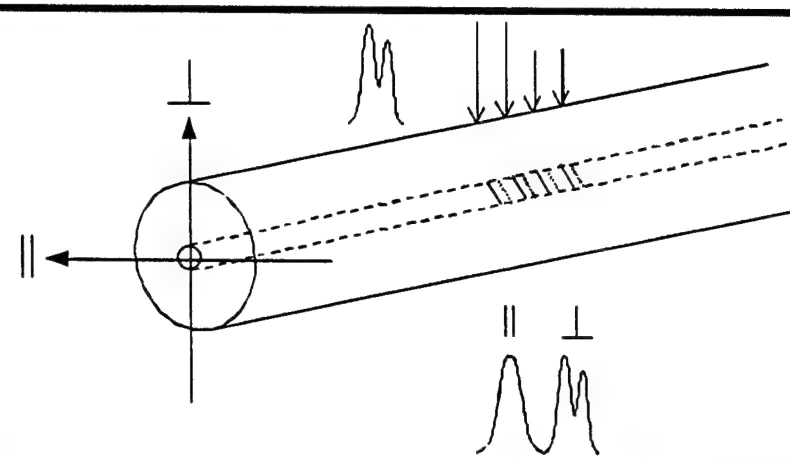


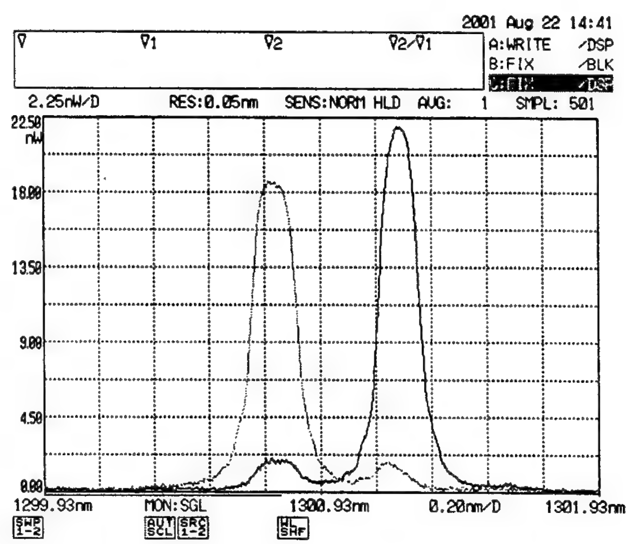


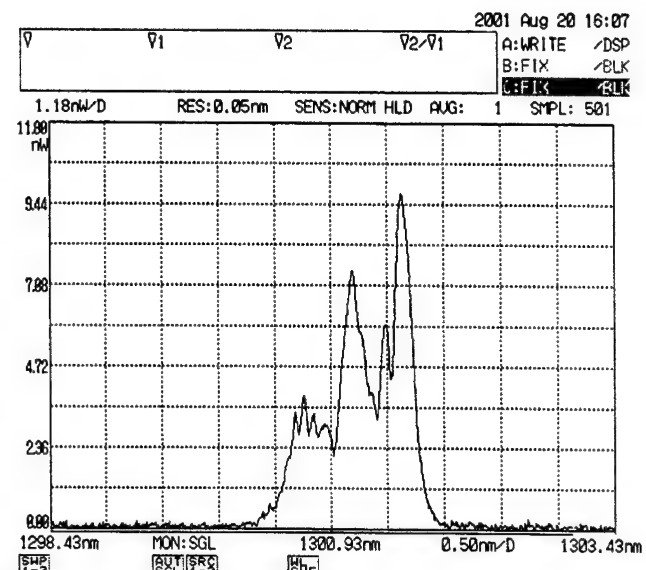
BLUE ROAD RESEARCH

Strain Measurement Interior to Composite Parts
Innovation in Science





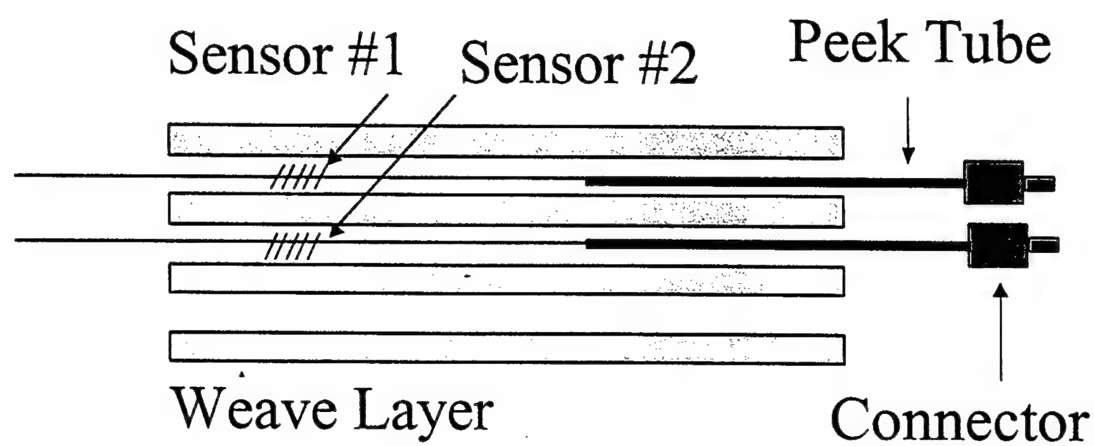




BLUE ROAD RESEARCH

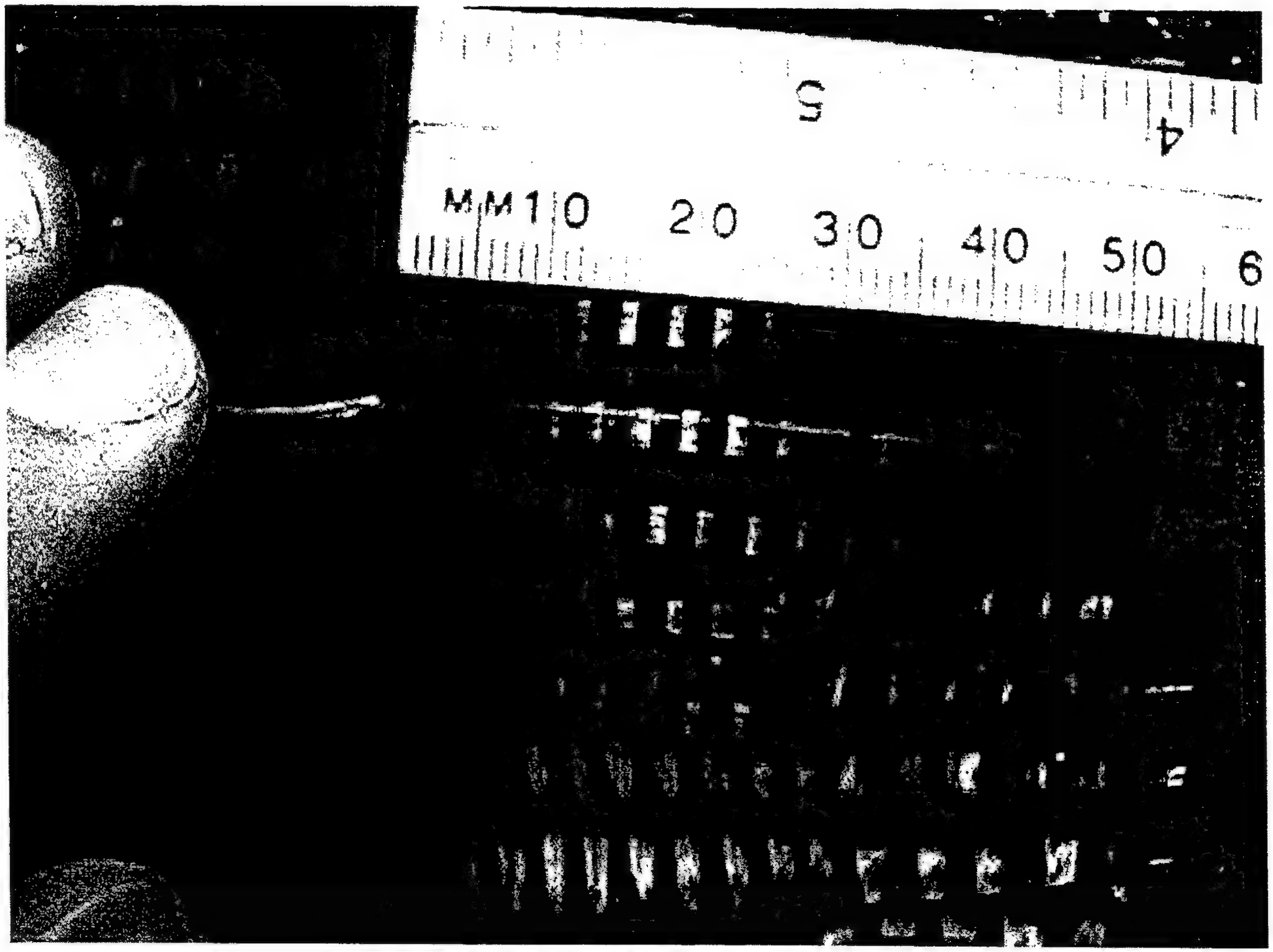
Initial Experiment

- A biaxial weave structure was used to support the fabrication of a small composite coupon for testing
- Multi-axis fiber gratings were placed in the four-layer coupon between the first and second layers and between the second and third layer



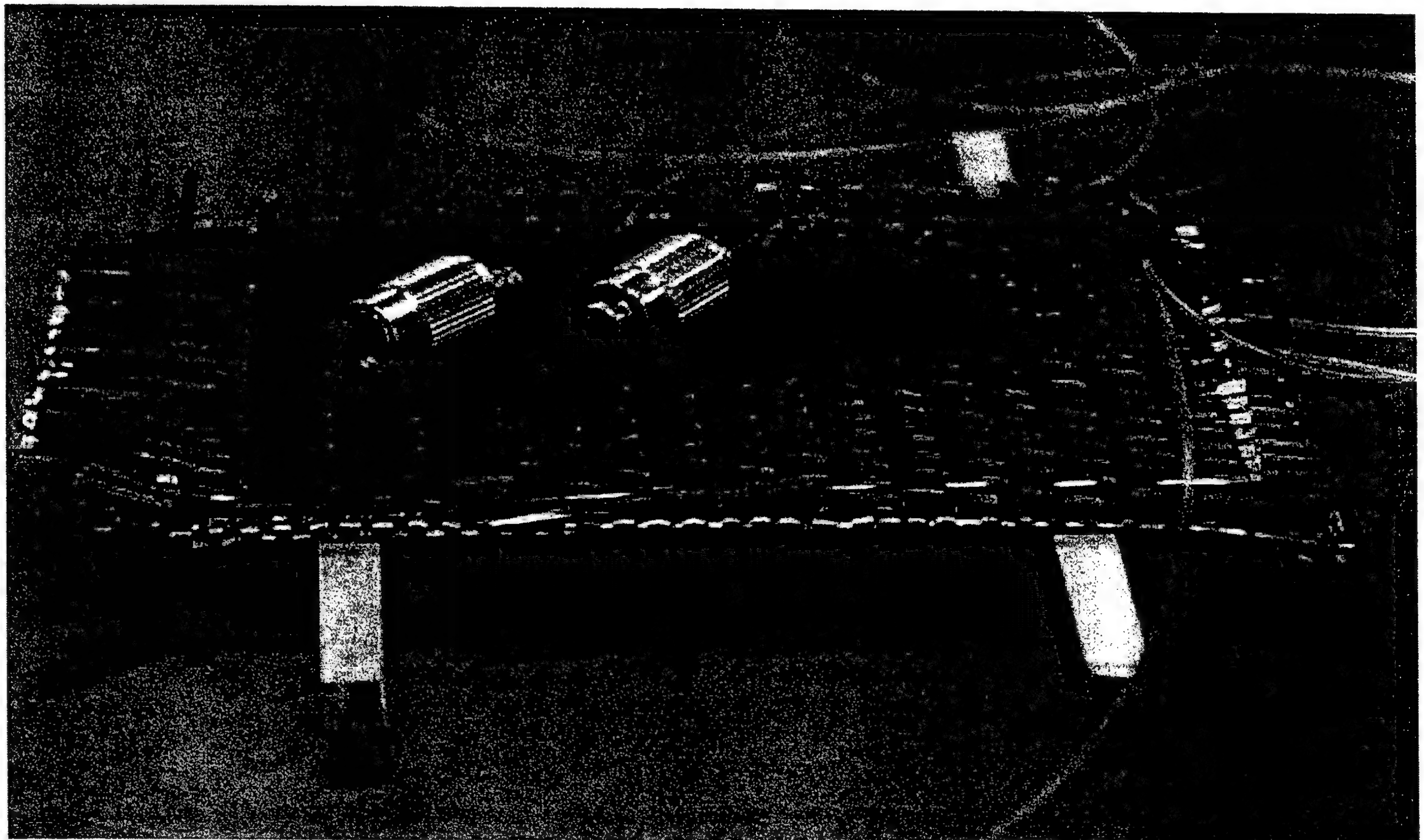
BLUE ROAD RESEARCH

Placement of Sensor



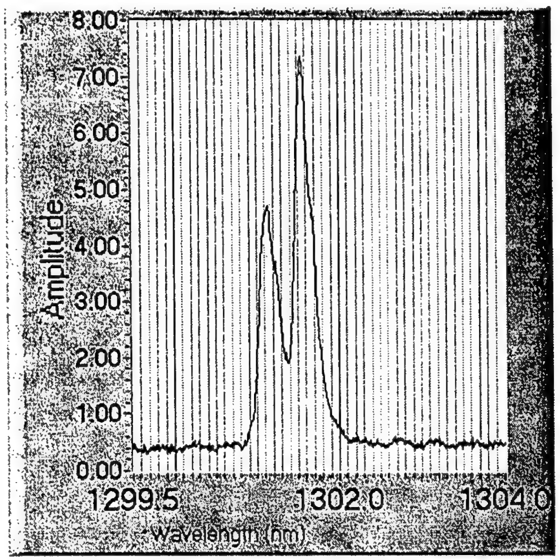
BLUE ROAD RESEARCH

Finished Composite Test Specimen

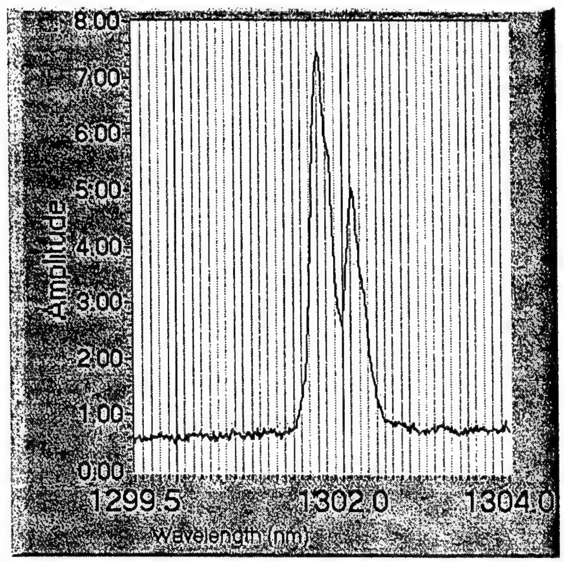


BLUE ROAD RESEARCH

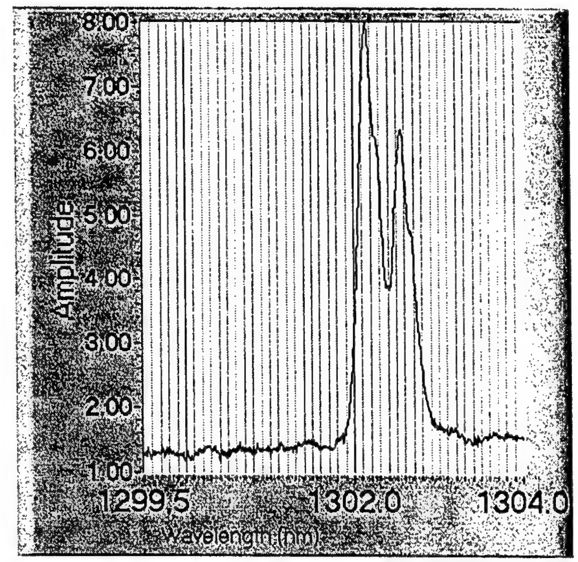
Monitoring Sensor #2 During the Cure Cycle: Increasing Temperature to Peak Temperature



0 min.



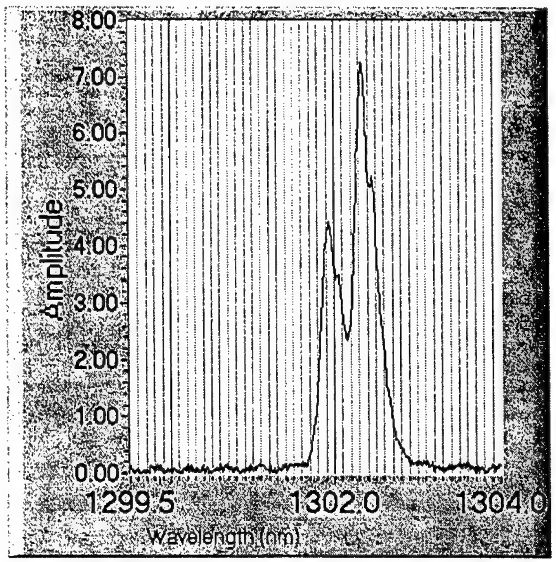
44 min.



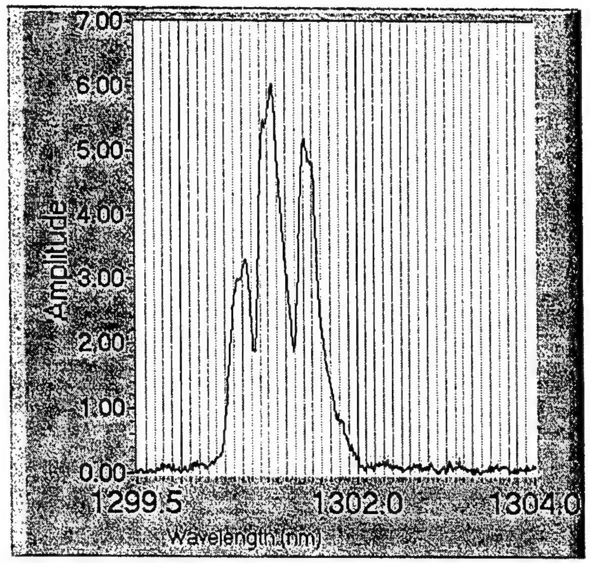
95 min.

BLUE ROAD RESEARCH

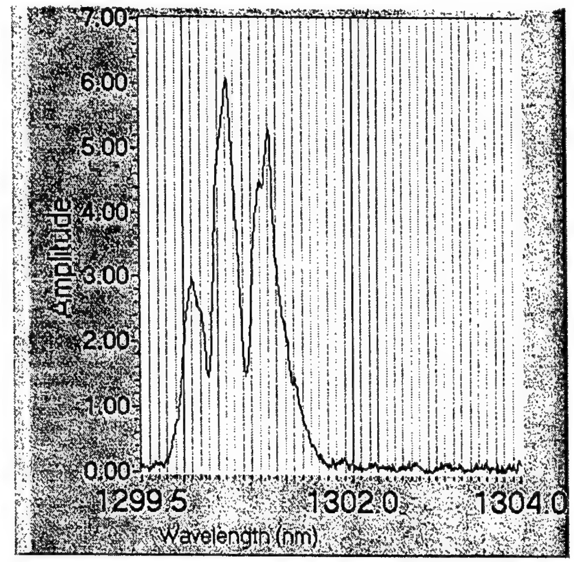
Monitoring Sensor #2 During the Cure Cycle: After Cross Linking/Cure and Cool Down



115 min.



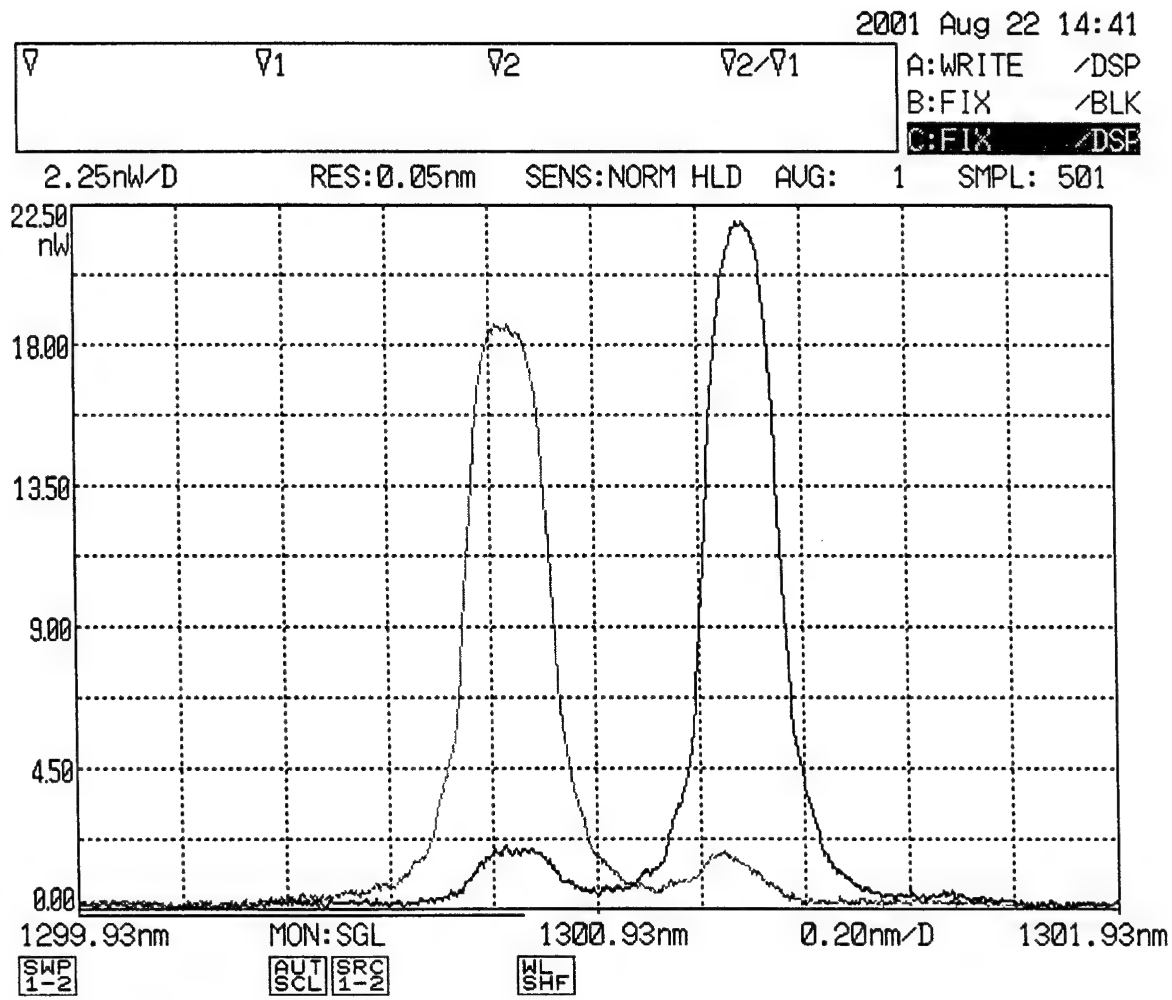
160 min.



200 min.

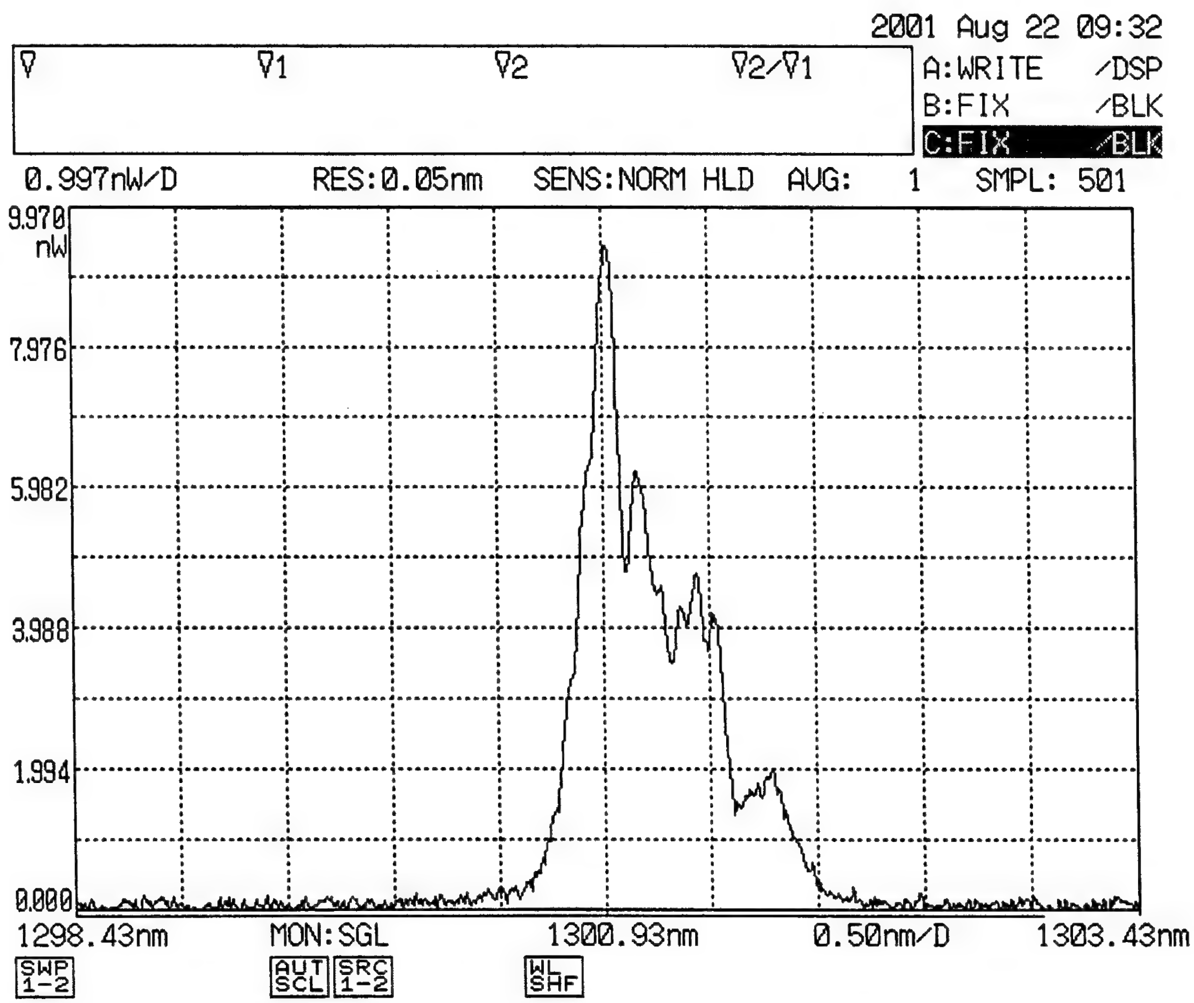
BLUE ROAD RESEARCH

Polarization Extinction



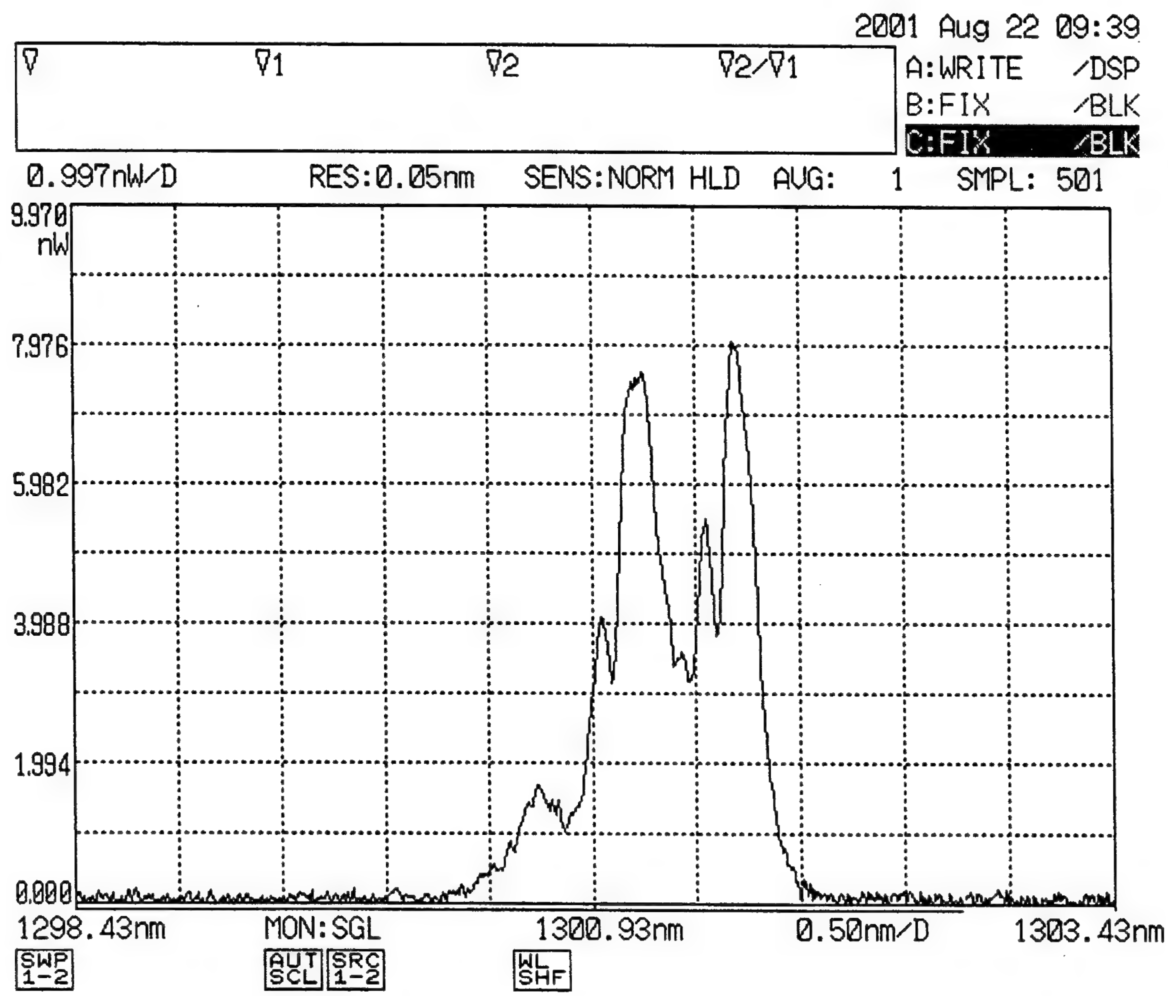
BLUE ROAD RESEARCH

Sensor #1: Shorter Wavelength



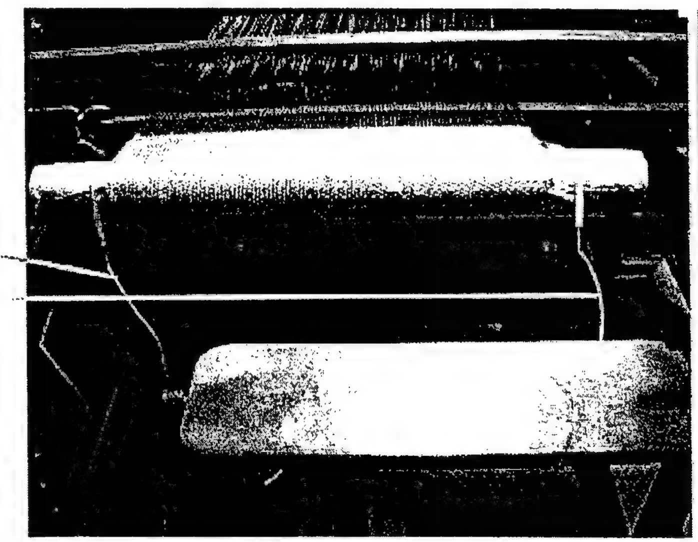
BLUE ROAD RESEARCH

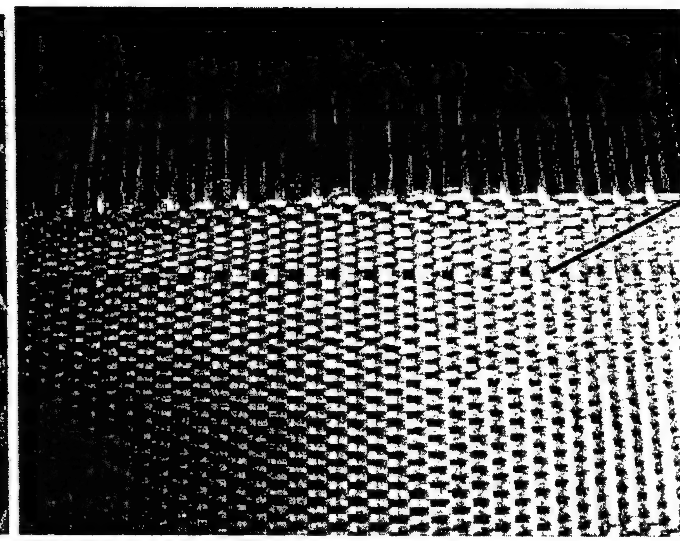
Sensor #1: Longer Wavelength



BLUE ROAD RESEARCH

Fabrication of Smart Fabrics





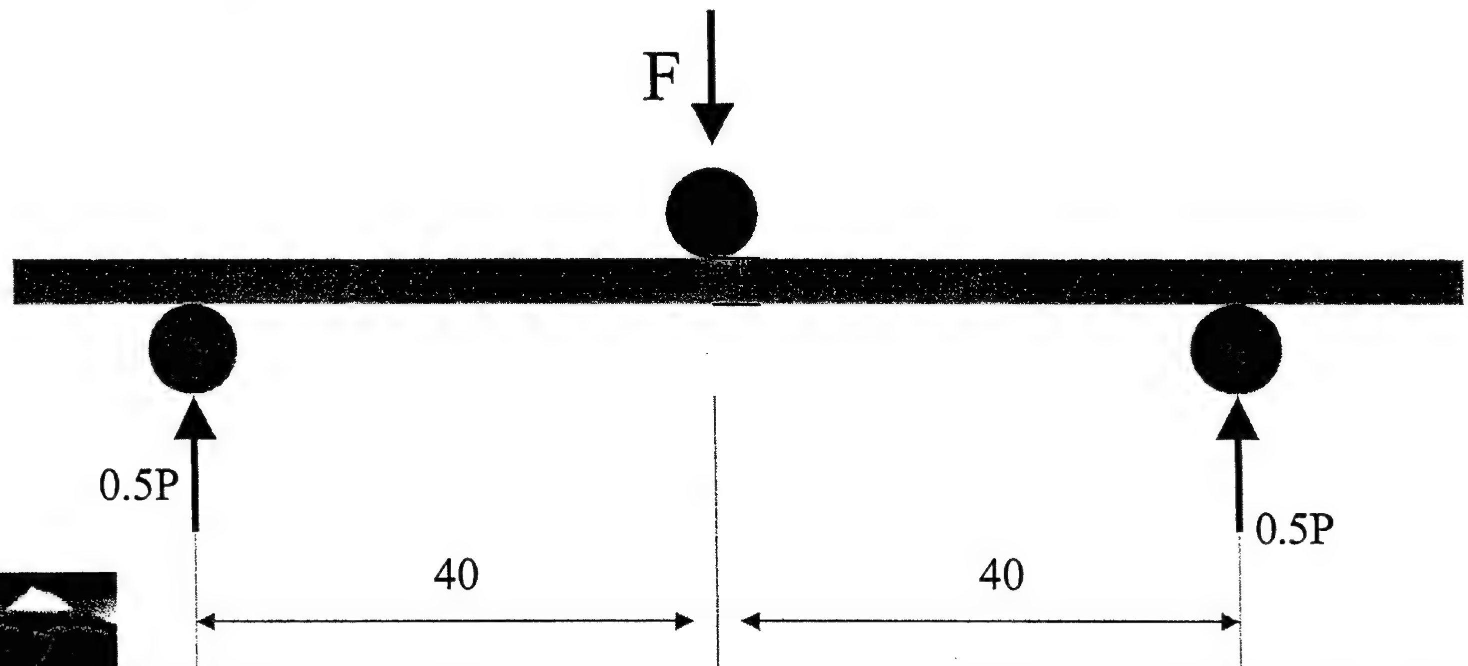
BLUE ROAD
RESEARCH

Single and Dual Axis Grating Sensors in E-glass/ Vinylester and E-glass/ Epoxy Composites

- Several panels were manufactured with single and multi-axis Bragg gratings using the Vacuum-Assisted Resin Transfer Molding (VARTM) process
- The response of the sensors in different stages of the VARTM process was recorded

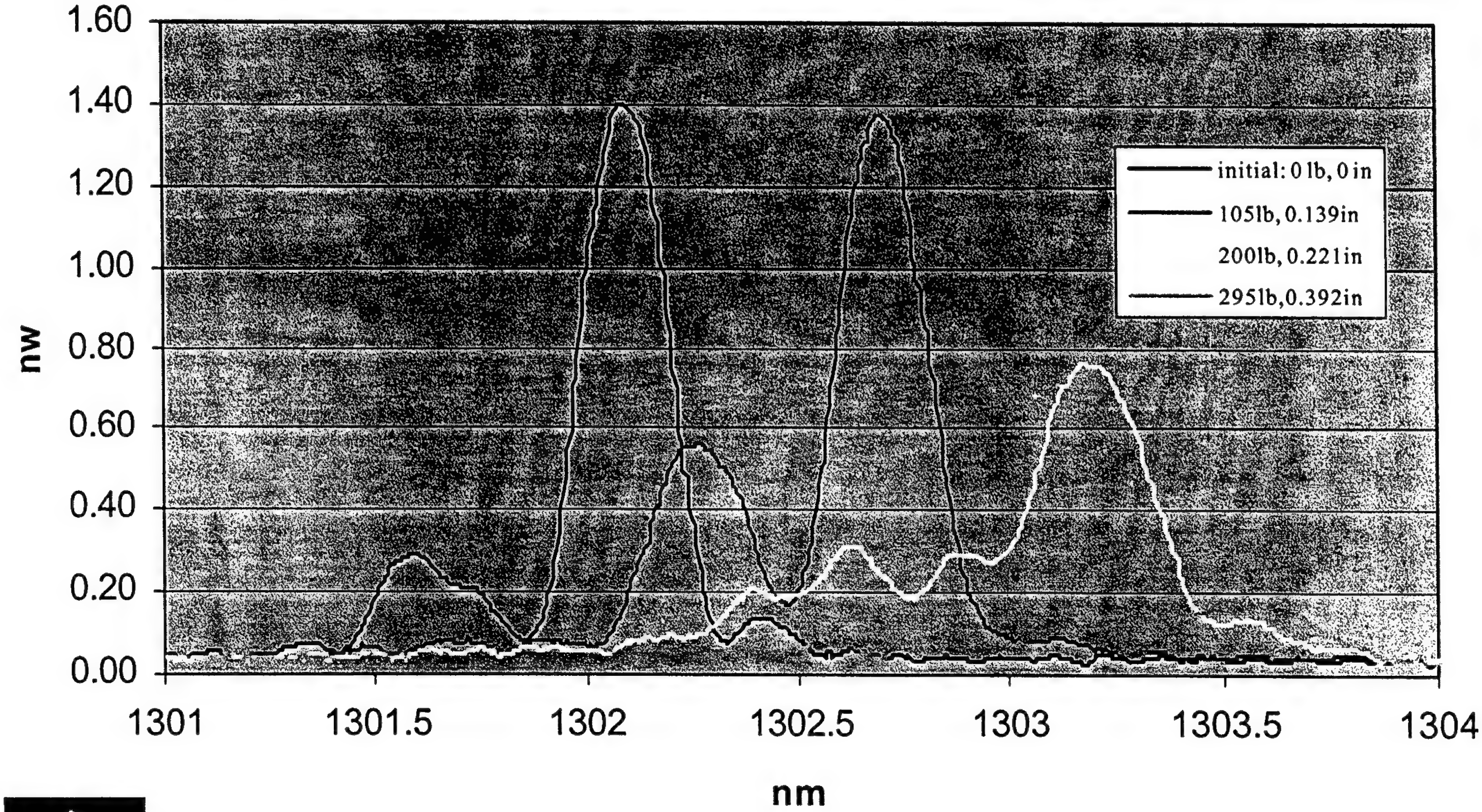
Mechanical Test Setup – Three Point Bend Test

- The specimens containing dual axis sensors were loaded by three point bending.
- The grating portion of the dual axis grating sensor was put beneath the load head.



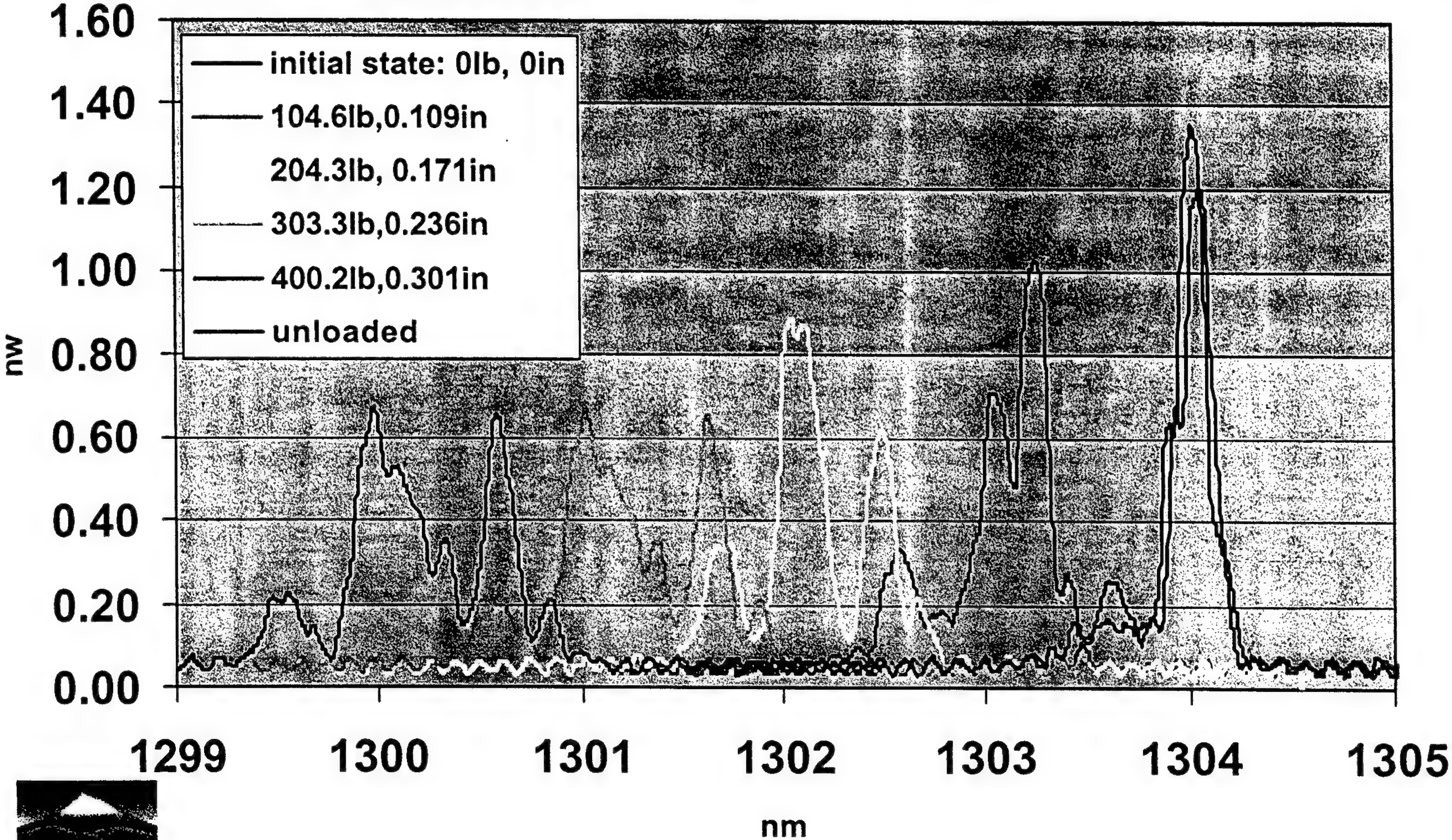
BLUE ROAD RESEARCH

Dual Axis FBG Sensor in E-glass/vinylester Composites Strained in Tension, Right Peak



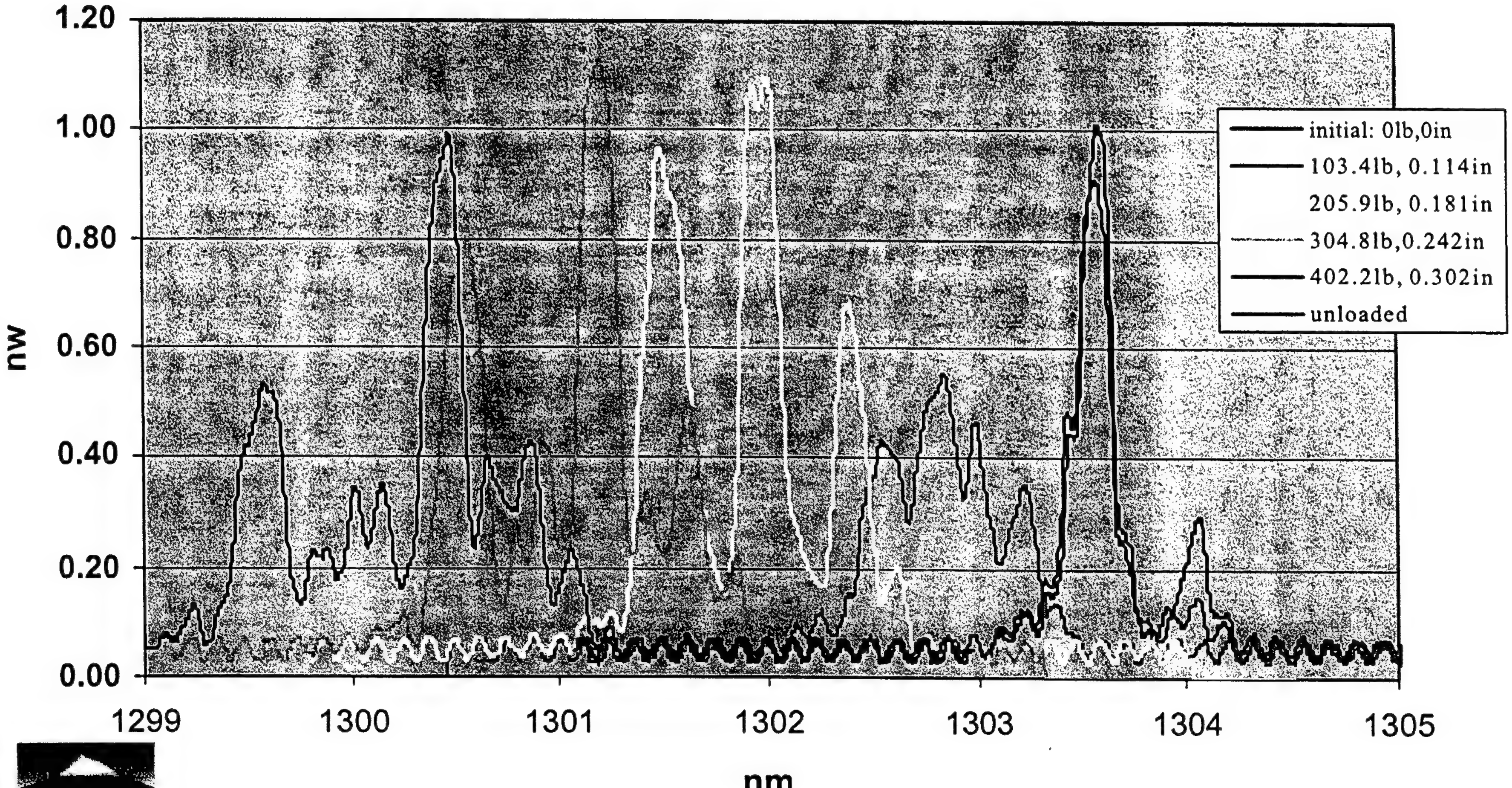
BLUE ROAD RESEARCH

Dual axis Grating Sensor in E-glass/epoxy Composites Strained in Compression, Right Peak



BLUE ROAD RESEARCH

Dual Axis FBG Sensor in Glass/epoxy Composites Strained in Compression, Left Peak



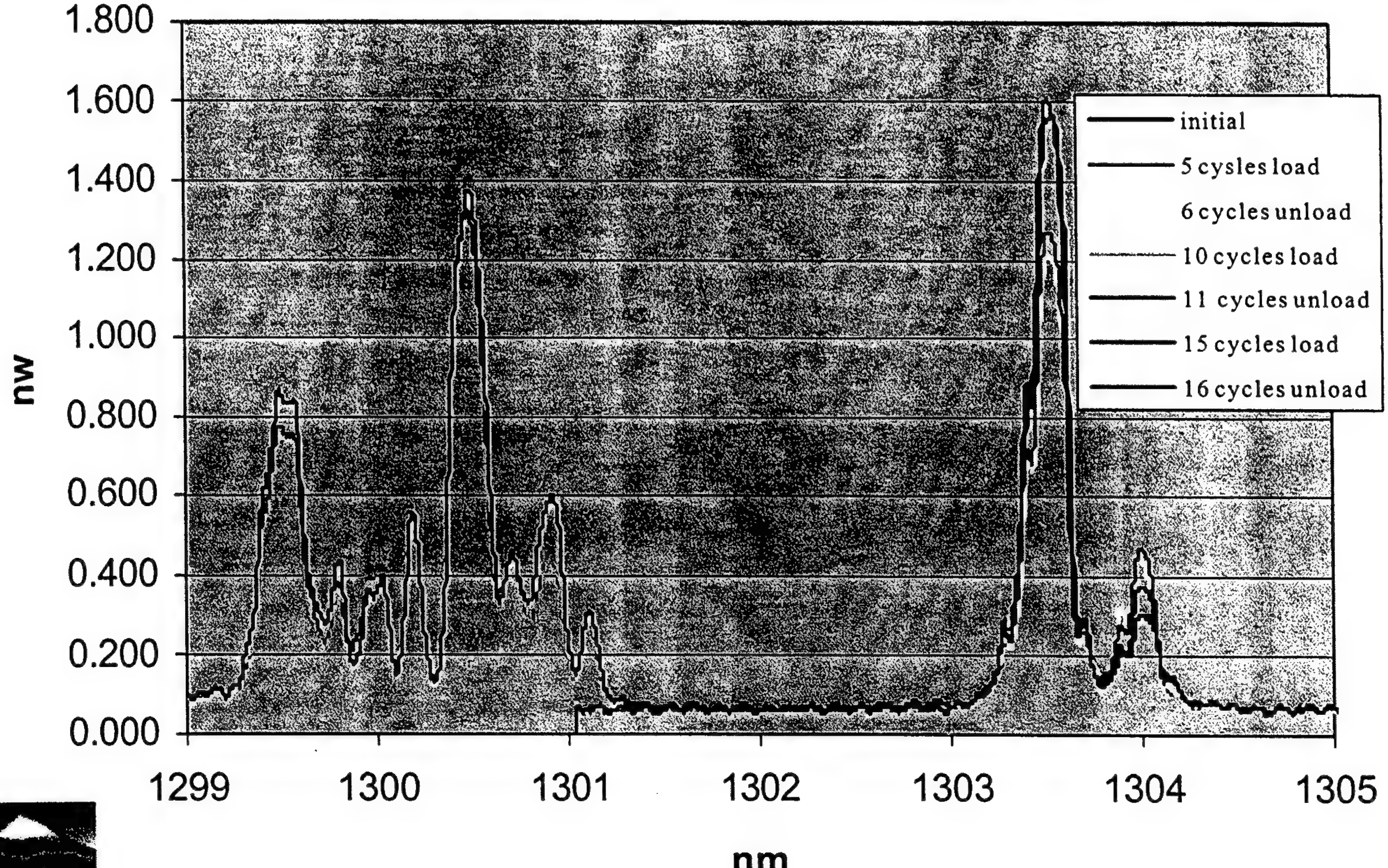
BLUE ROAD RESEARCH

Repeatability and Drop Test

- Repeatability of the dual axis FBG sensor embedded in textile composites was evaluated using a loading-unloading cycle test.
- The results demonstrated that the signal from the dual axis FBG sensor is repeatable.
- A drop weight impact test was performed, only a small permanent deformation (strain) was formed by the impact

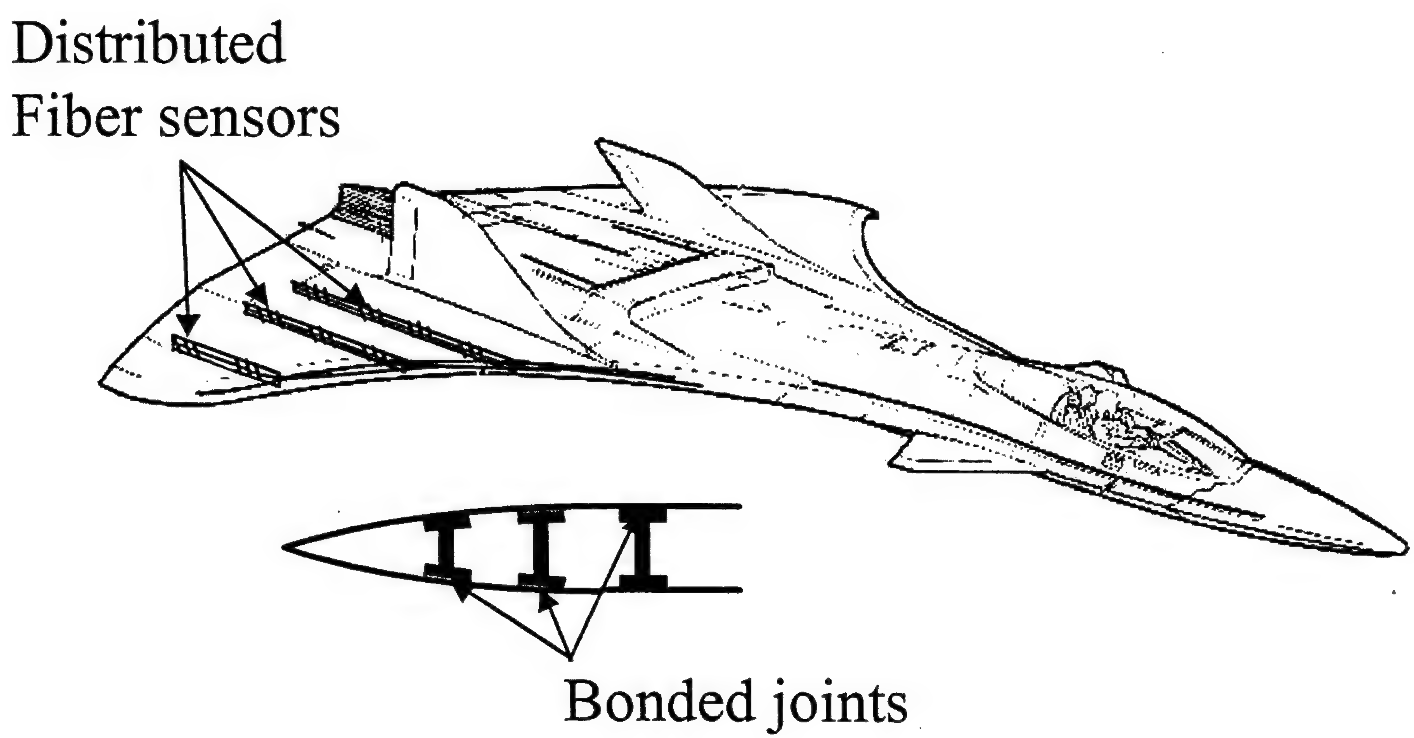
BLUE ROAD RESEARCH

Dual axis FBG sensor in glass/epoxy composites under cyclic compressive loading-unloading (0lb-400lb), left peak



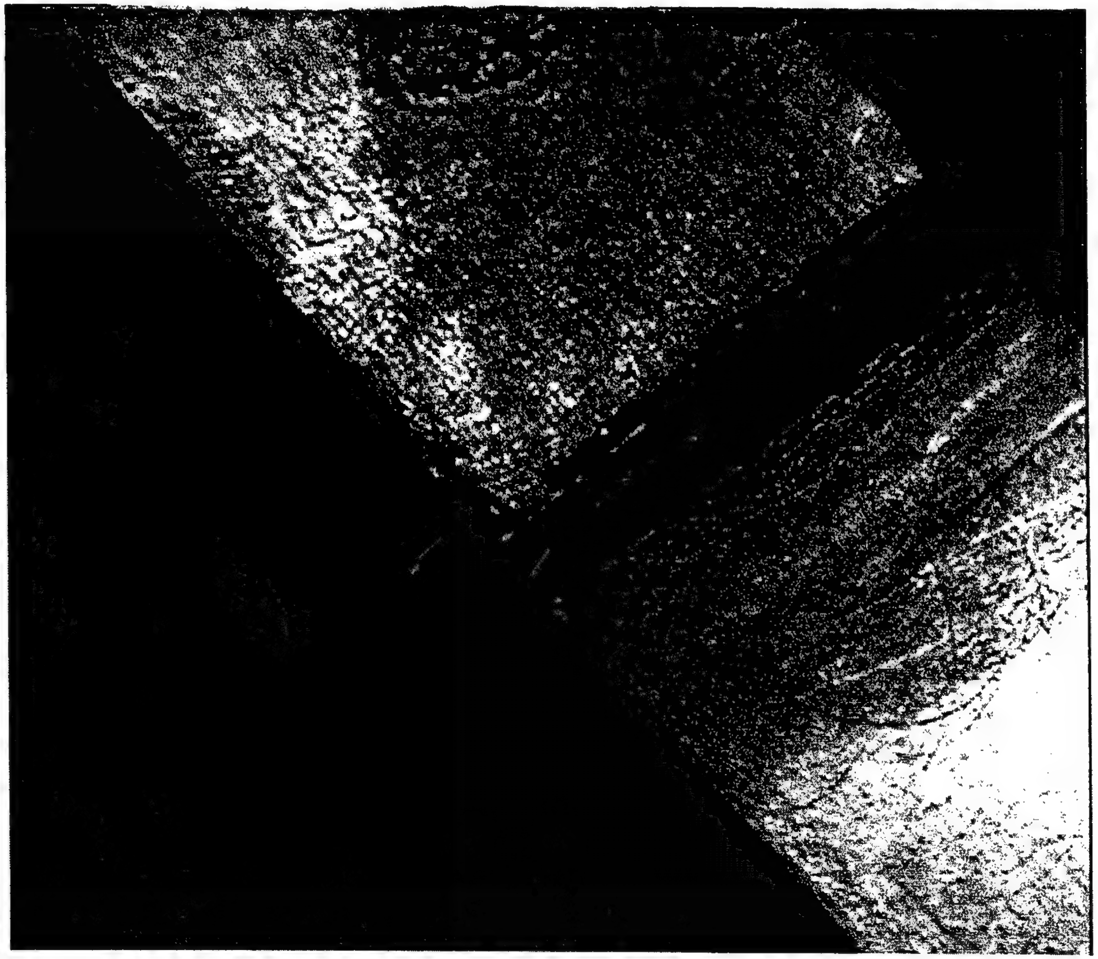
BLUE ROAD RESEARCH

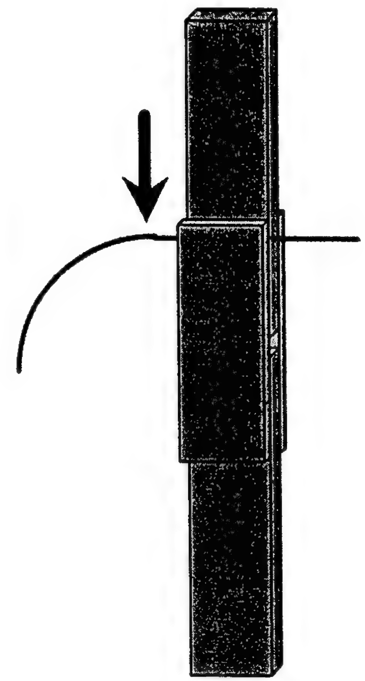
Bonded Joint Health Monitoring System



BLUE ROAD RESEARCH

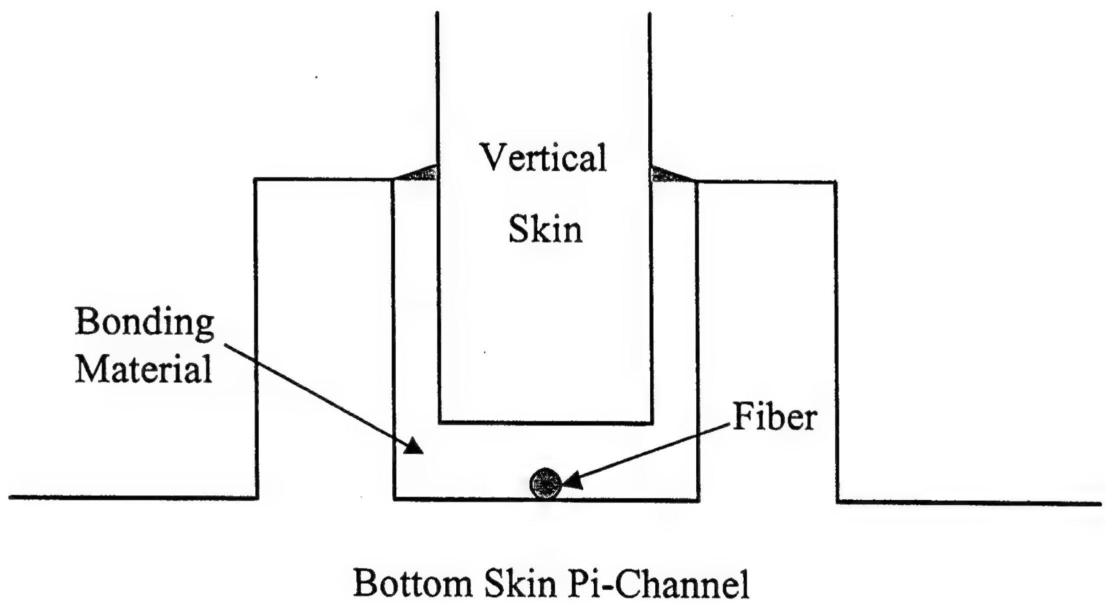
Joint Instrumented for Shear





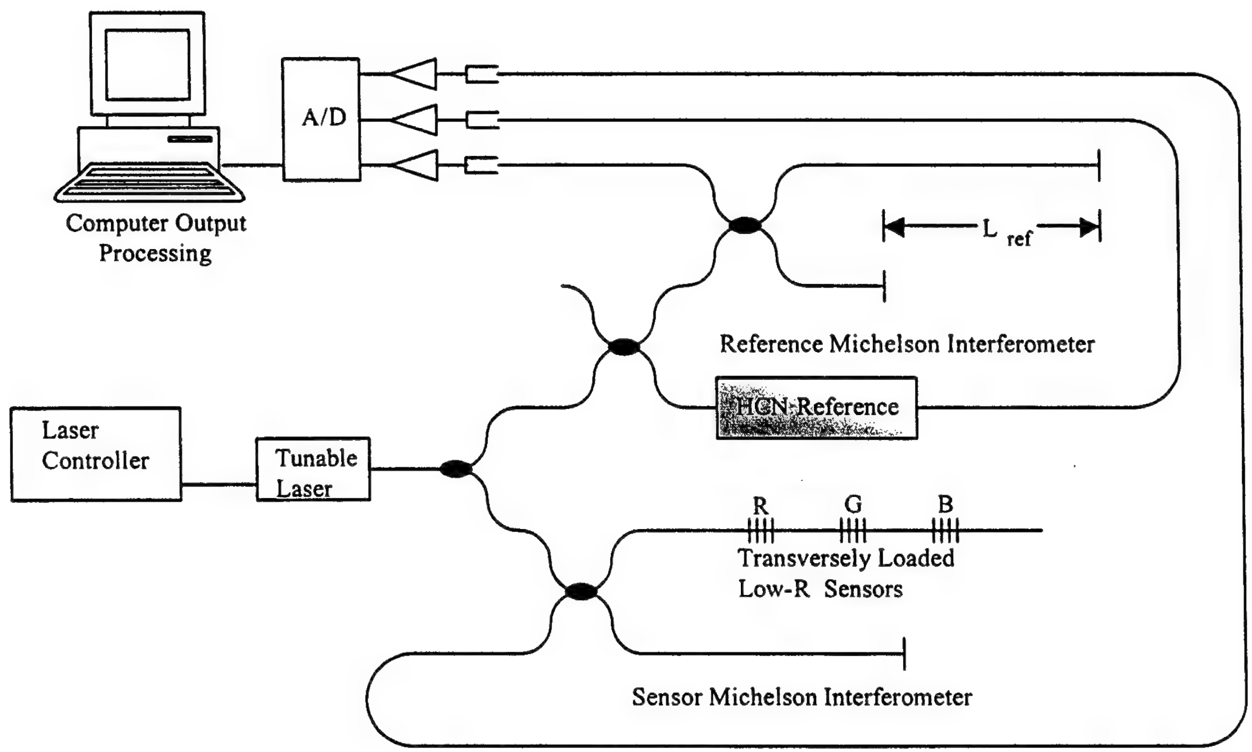
BLUE ROAD RESEARCH

Pi-Channel Multi-Axis Strain Monitoring



BLUE ROAD RESEARCH

High Density Fiber Grating Strain Sensor System



BLUE ROAD RESEARCH

Composite Structures Summary

- Simultaneous measurement of axial and transverse strains
- Measurement of sub-grating strain distributions for "simple" conditions in weave structures
- Useful for structural monitoring during part formation and subsequent loading

BLUE ROAD RESEARCH

Composite Structures Systems Development

- Demonstrate static ground testing. Compare baseline loaded and unloaded strain signatures with current readings to detect structural damage.

- Evolve monitoring equipment to dynamic, low-power, rugged, compact system for in-flight monitoring.

Ongoing Improvements in System Capability

- Develop theory and modeling tools to better link multi-axis strain measurements to structural behavior.

- Use WDM and interferometric techniques to multiplex hundreds of sensors on single line.

- Develop algorithms to translate complicated multiple peak structures into highly spatially resolved multi-axis strain measurement.

FAST SELF COOLING MECHANISMS

Roger J. Morgan and Sai Lau

Texas A&M University

AFOSR WORKSHOP ON MULTIFUNCTIONAL AEROSPACE MATERIALS

24th OCTOBER 2002

THEME

- "OUT OF THE BOX"
  - SURFACE COOLING CONCEPTS
  - THERMAL ABLATION RESISTANT STRUCTURES

- GOALS
  - RAPID TEMPERATURE - TIME COOLING
    - LIMIT IR-TIME SIGNATURES

  - ENHANCED THERMAL RESISTANT STRUCTURES-PROCESSIBLE COATINGS AND STRUCTURES

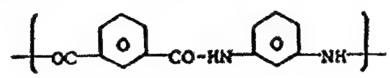
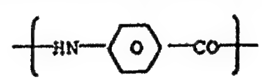
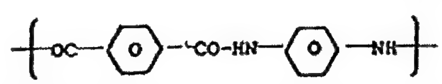
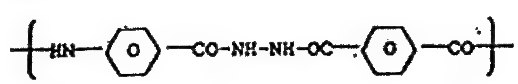
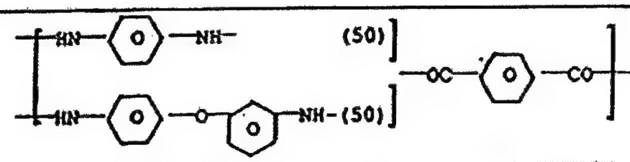
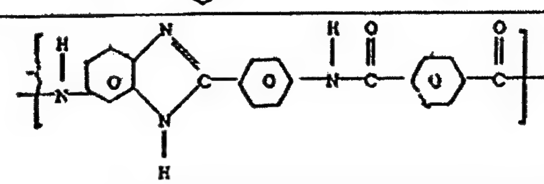
SUBJECT MATTER

- HISTORY
  - LASER HARDENING MECHANISMS
    - HIGH MOISTURE BEARING FIBERS (FIBER -S)
    - TUNGSTEN CARBIDE, TANTALUM CARBIDE IN-SITU SERVICE ENVIRONMENT FORMATION
- SURFACE MOISTURE EVAPORATION
  - SKIN COOLING MECHANISM
  - MICROFLUIDICS
- THERMAL CONDUCTION - INTERNAL COOLING “PIPES”
- RAPID SUPER - THERMAL CONDUCTORS
- COATING SELF COOLING MECHANISMS (IN-SITU REPLENISHMENT)

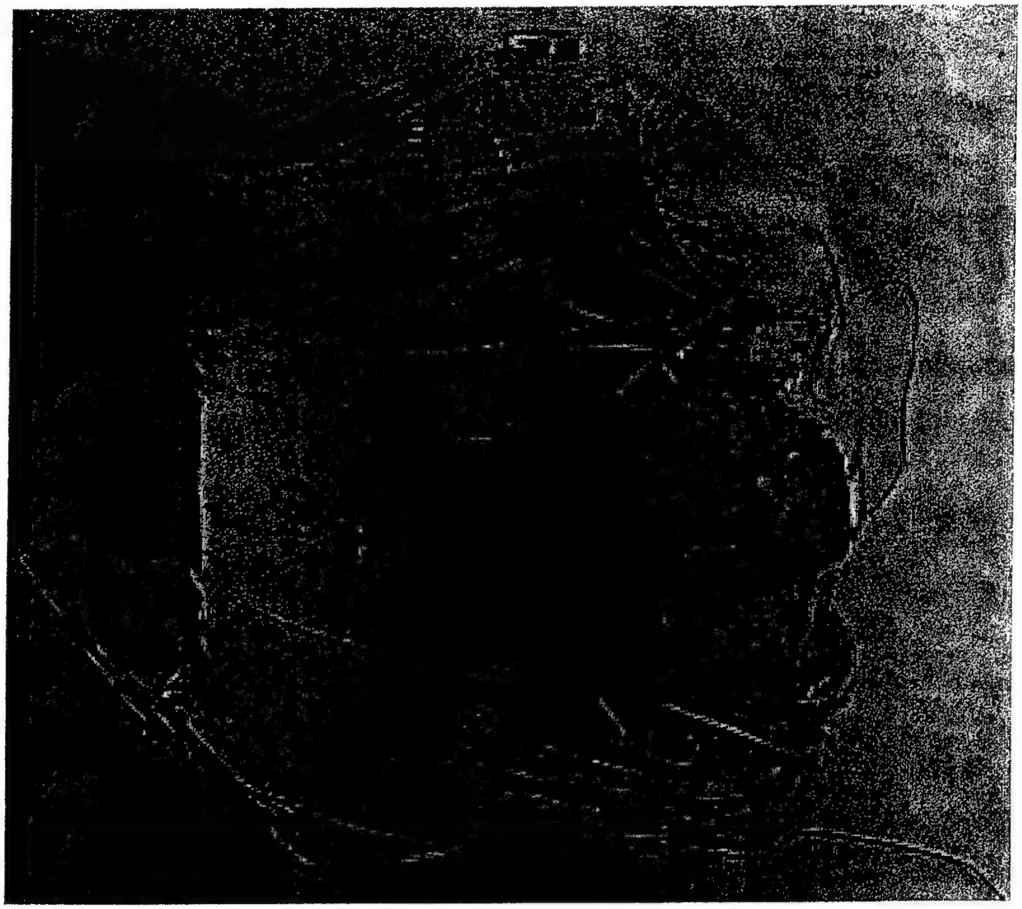
Table 1

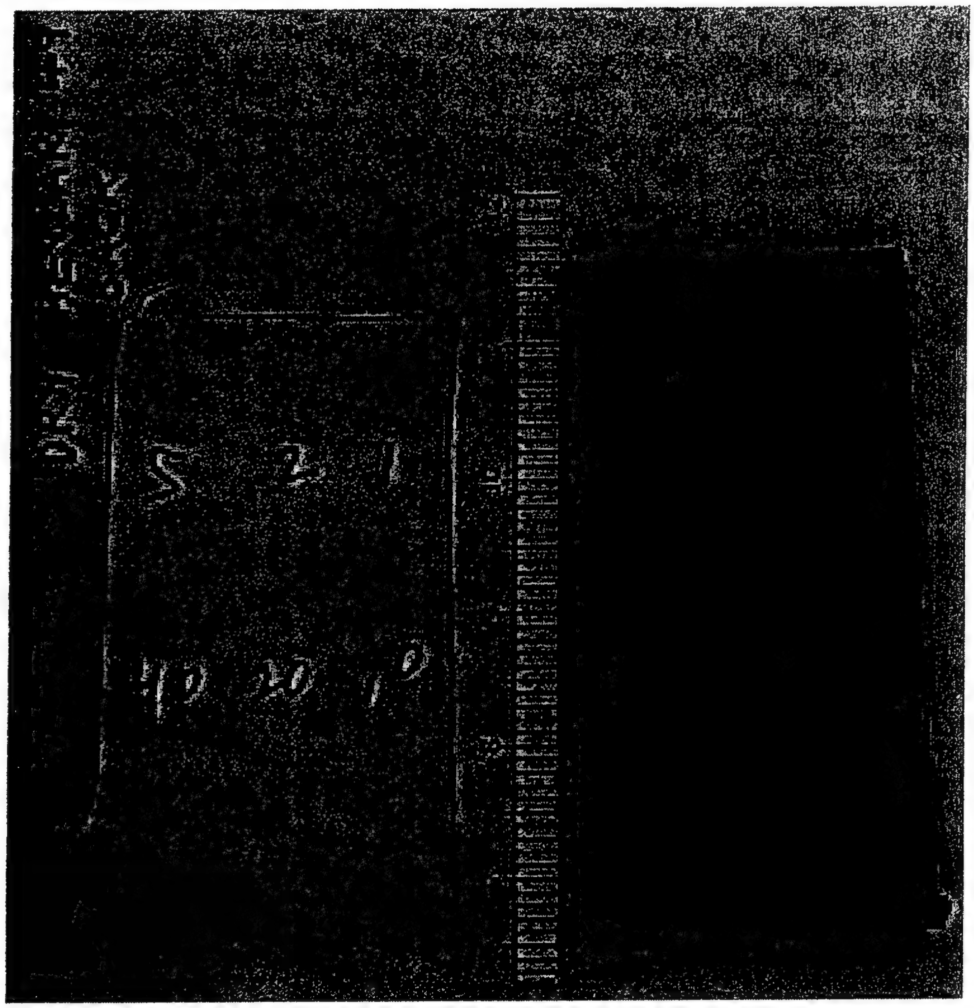
Aromatic Polyamides That Were Developed

for Commercial Fiber Production

Chemical Name (abbreviation)	Chemical Structure	Trade Name (company)
poly(m-phenyleneisophthalamide) (PmPI)		Nomex™(du Pont); Conex™(Teijin)
polybenzamide (PBA)		PRD 49-1™* (Du Pont)
poly(p-phenylene terephthalamide) (PPTA)		Kevlar™(du Pont); Twaron™ (Akzo N.V.)
polyterephthaloyl-p-aminobenzhydrazide (PABH-T)		X-500™* (Monsanto)
copolyterephthalamide of p-phenylenediamine and 3,4' diamino-diphenyl ether (CPTA)		HM-50™; Technora™ (Teijin)
polyamidobenzimidazole (PABI)		FVM™ (USSR)

*No longer commercially produced.





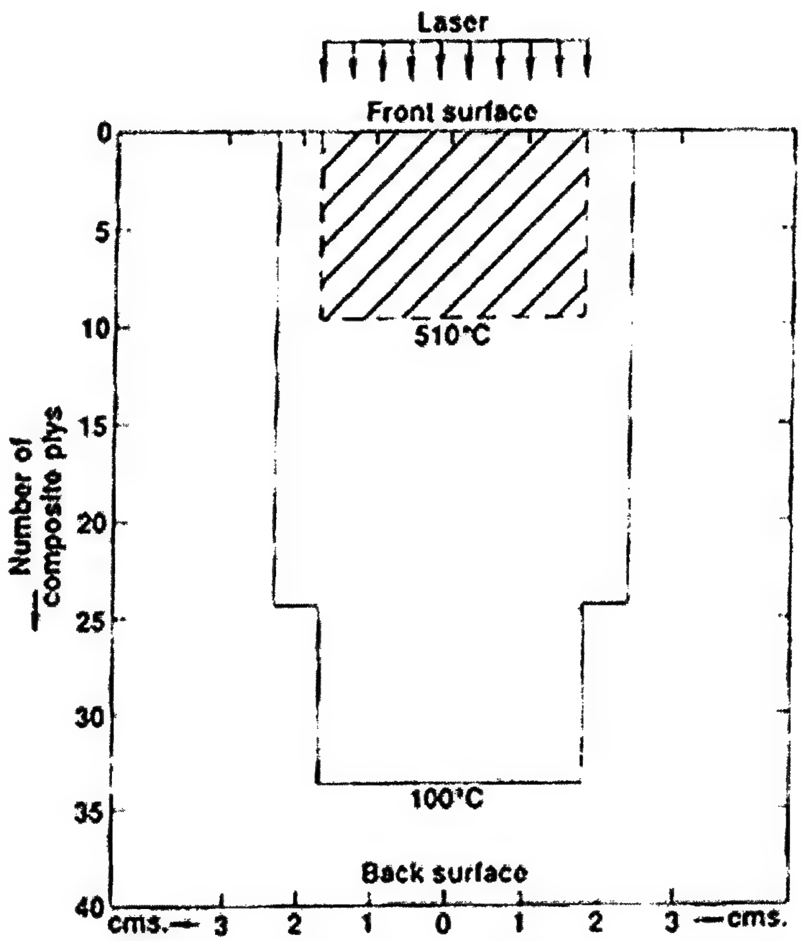
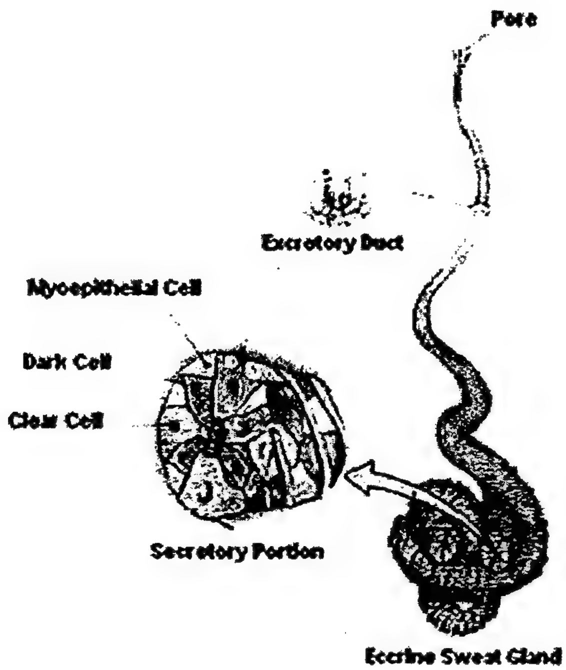


Figure 11. The 100°C and 510°C two-dimensional temperature contours in a 40 ply carbon fiber-epoxy composite after 10 s exposure to a 600 W/cm², 3.5 beam diameter laser.

THE MECHANISM OF ECCRINE SWEAT EXPULSION

Eccrine sweat glands are simple coiled tubular glands located in the deep dermis or underlying hypodermis and are present throughout the body. Their primary function is evaporative cooling.



1. They develop as invaginations of the epithelium of the dermal ridge. They grow into the dermis with its deep aspect becoming the glandular portion of the seat gland.
2. Eccrine sweat glands are simple coils of cuboidal epithelium containing two kinds of cells.
   A. **Dark cells** produce sialo mucins.
   B. **Clear cells** produce water and electrolytes.
3. The final production is hypotonic (99% water)
4. Adult produce between 0.5-10 leters/day.

CONDUCTIVITY MODEL

ASSUMPTIONS:

- The outer surface is heated instantaneously to 100 °C before cooling begins
- Inner surface temperature is maintained at 25 °C
- There is no cooling to atmosphere
- Water flow is semi-turbulent

GOVERNING EQUATION:

(HEAT ADDED -HEAT CONDUCTED ACROSS THE MATERIAL) PER cm^2 PER s =
(HEAT INCREASE IN THE MATERIAL PER cm^2 PER s)

EVAPORATION MODEL

ASSUMPTIONS:

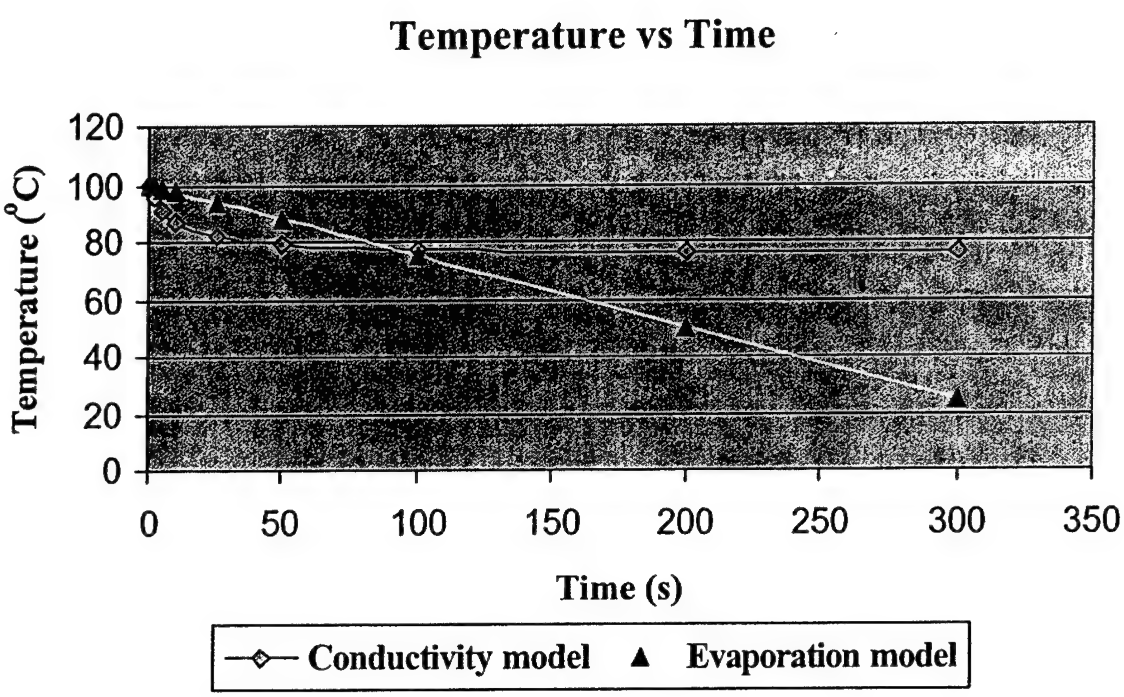
? Pore openings cover 50% of surface area

? 0.2 kg. Of water evaporates per second per square cm. of surface area

? Material and water properties are considered at conditions prevailing at an altitude of approximately 60,000 ft.

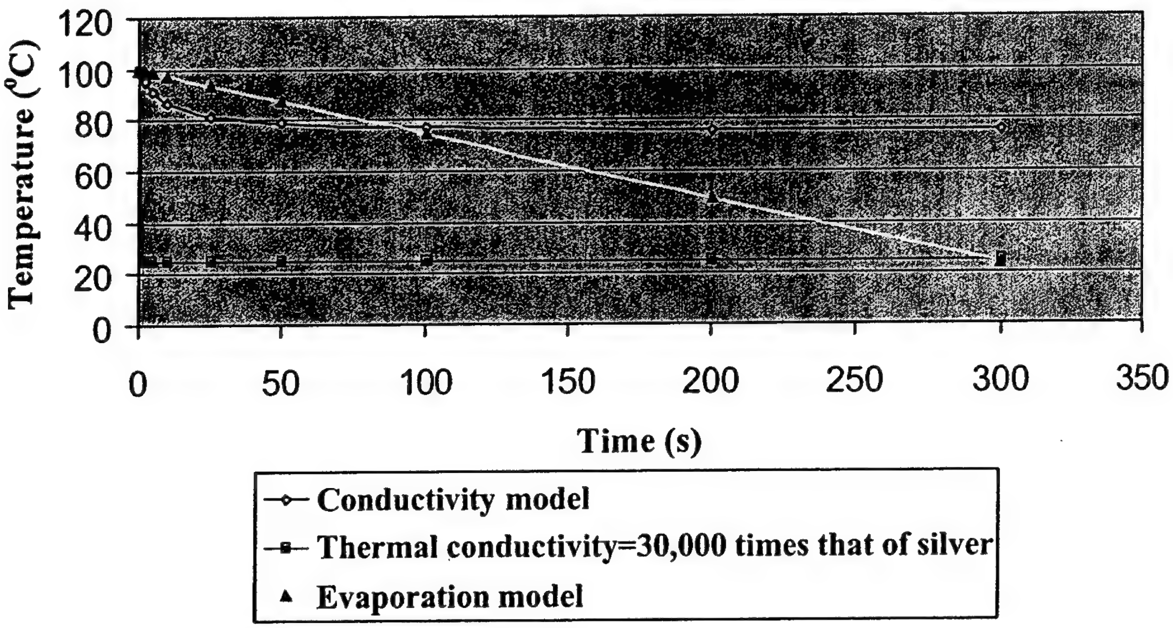
GOVERNING EQUATION:

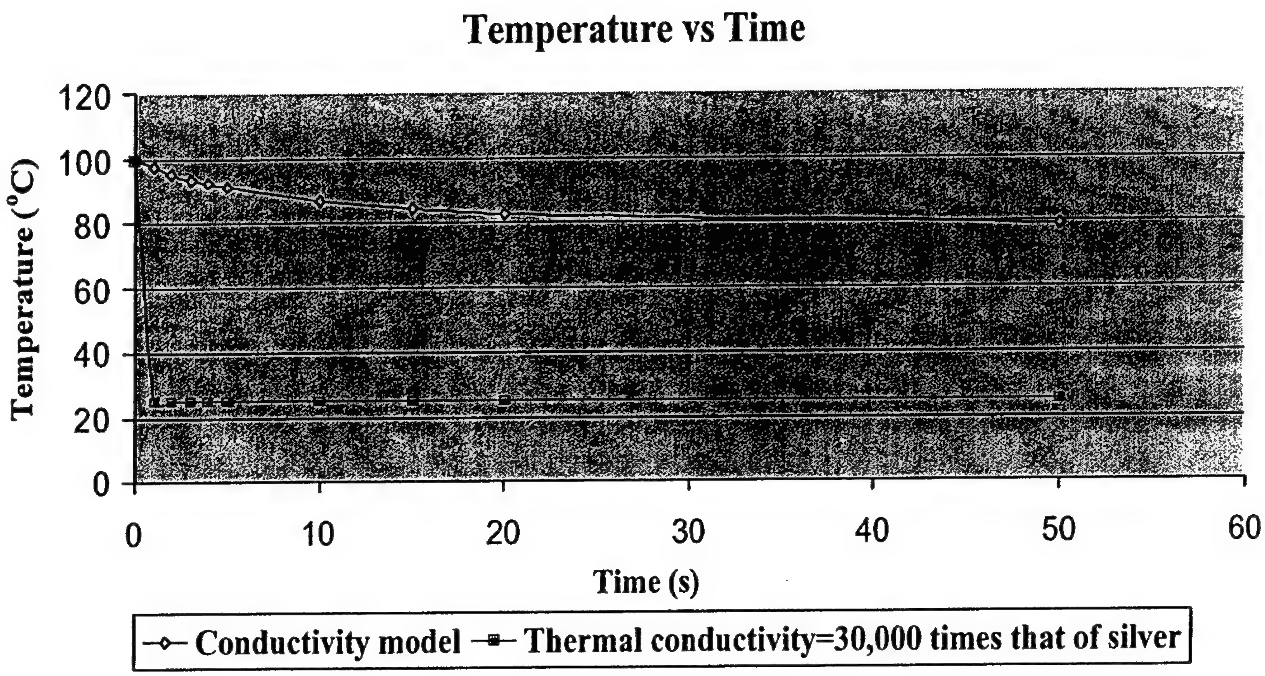
(HEAT ADDED -HEAT TAKEN AWAY BY EVAPORATION) PER cm^2 PER s =
(HEAT INCREASE IN THE MATERIAL PER cm^2 PER s)



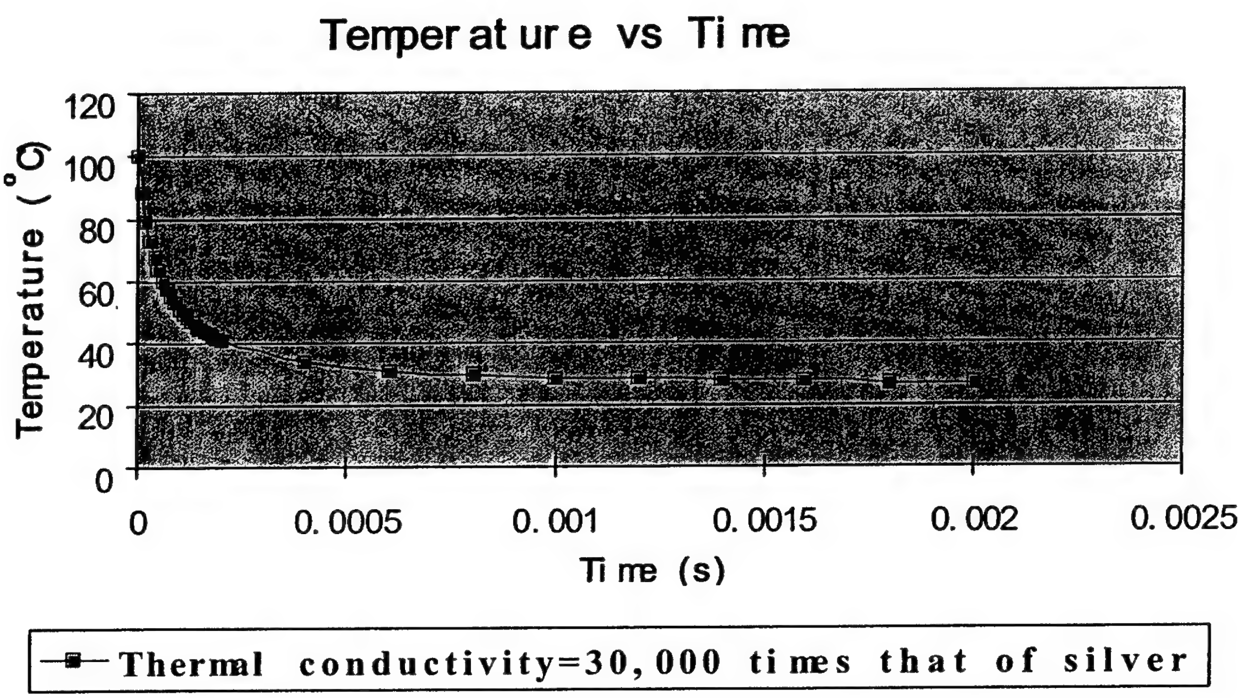
Temperature vs Time
120
100
80
60
40
20
0
Temperature (^oC)
0
50
100
150
200
250
300
350
Time (s)
Conductivity model
Evaporation model

Temperature vs Time for different methods of cooling





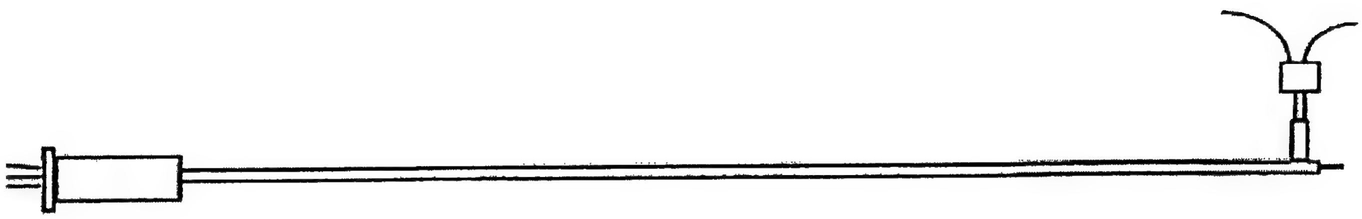
Temperature vs Time
Temperature (°C)
120
100
80
60
40
20
0
0
10
20
30
40
50
60
Time (s)
Conductivity model
Thermal conductivity=30,000 times that of silver



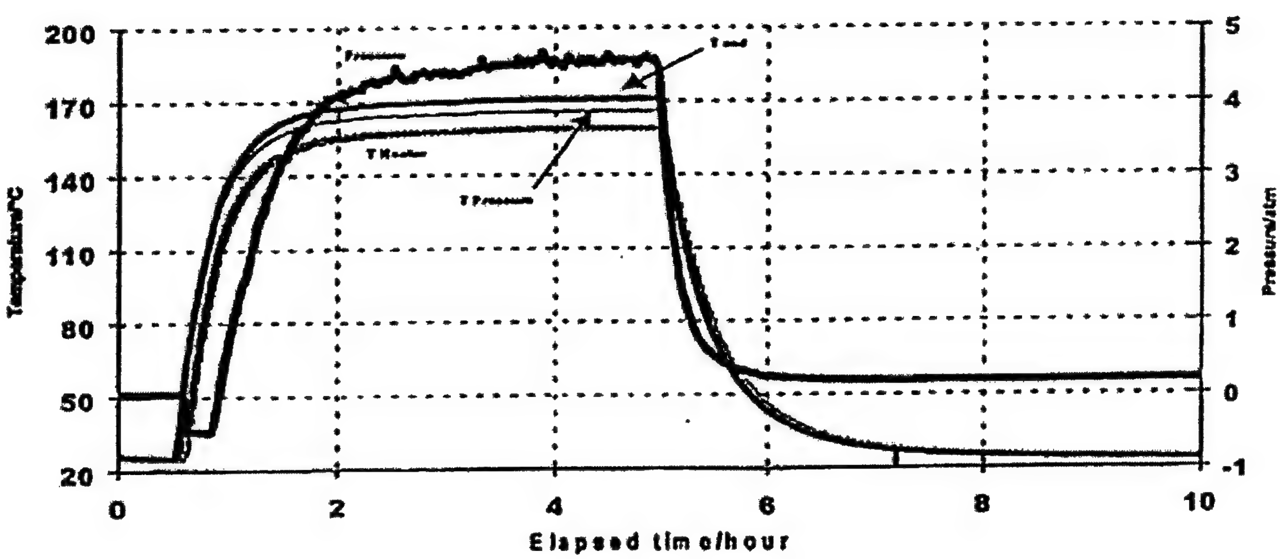
Temperature vs Time
Temperature (°C)
120
100
80
60
40
20
0
0
0.0005
0.001
0.0015
0.002
0.0025
Time (s)
Thermal conductivity=30,000 times that of silver

SUPER THERMAL CONDUCTOR

- COPPER SEALED TUBE - 5 MM D
- AIR 0.5 ATMOSPHERE
- 3 COATINGS - 0.1 MM THICK
  - OXIDES
  - CHROMATES
- UP TO 3 x 10 THERMAL CONDUCTIVITY OF SILVER



Supertube with pressure transducer attached.



Pressure and temperature inside an operating Supertube.

Graphitic Foam as Heat Carrier For Thermal Control in Phase Change Materials (PCM) Composite Systems

Khalid Lafdi

University of Dayton Research Institute
300 College Park, Dayton OH. 45469-0168 USA

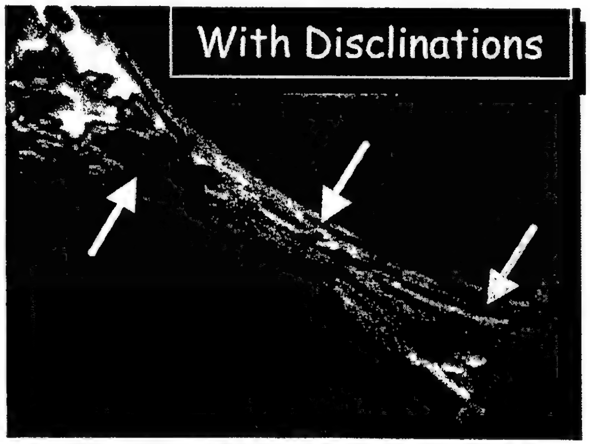
Materials & Manufacturing Directorate,
AFRL/MLBC, WPAFB, OH 45433 USA

Khalid.lafdi@wpafb.af.mil

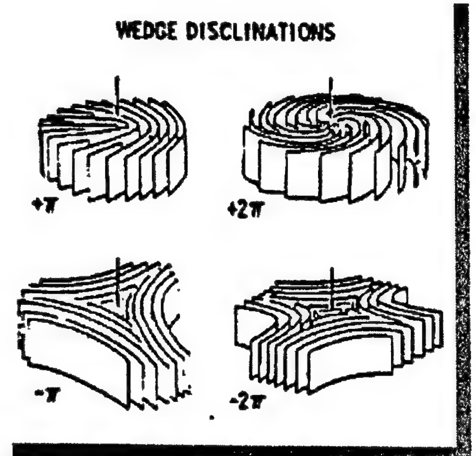
UDRI
UNIVERSITY of DAYTON RESEARCH INSTITUTE

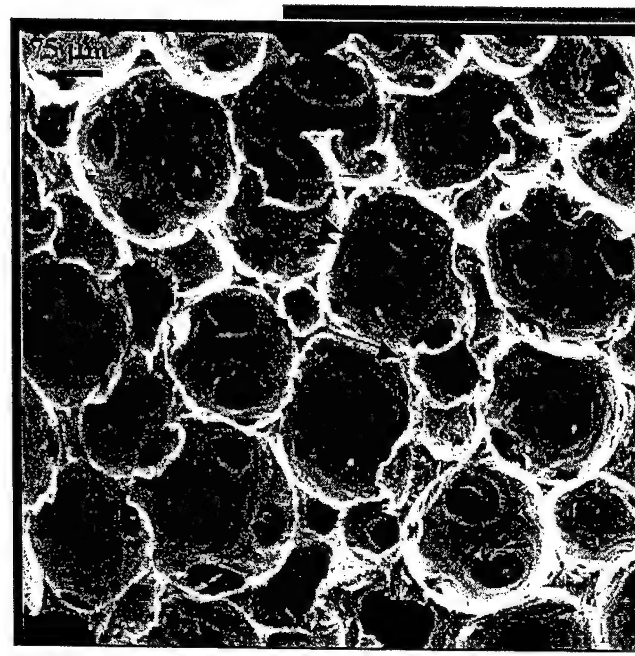
ITAR restricted

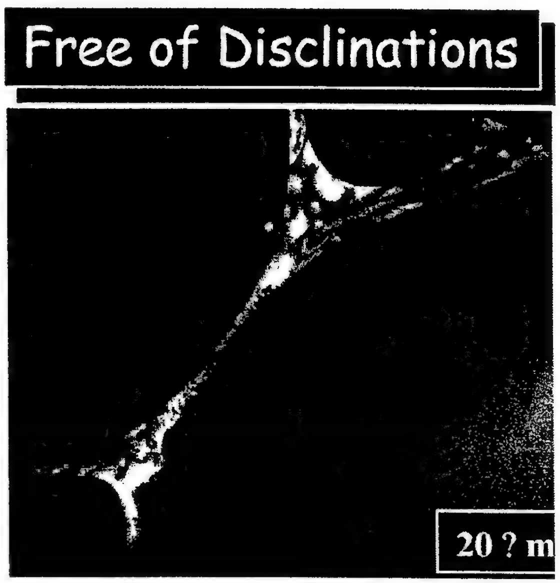
Microscopy Characterization of Graphitic Foam



Ligaments

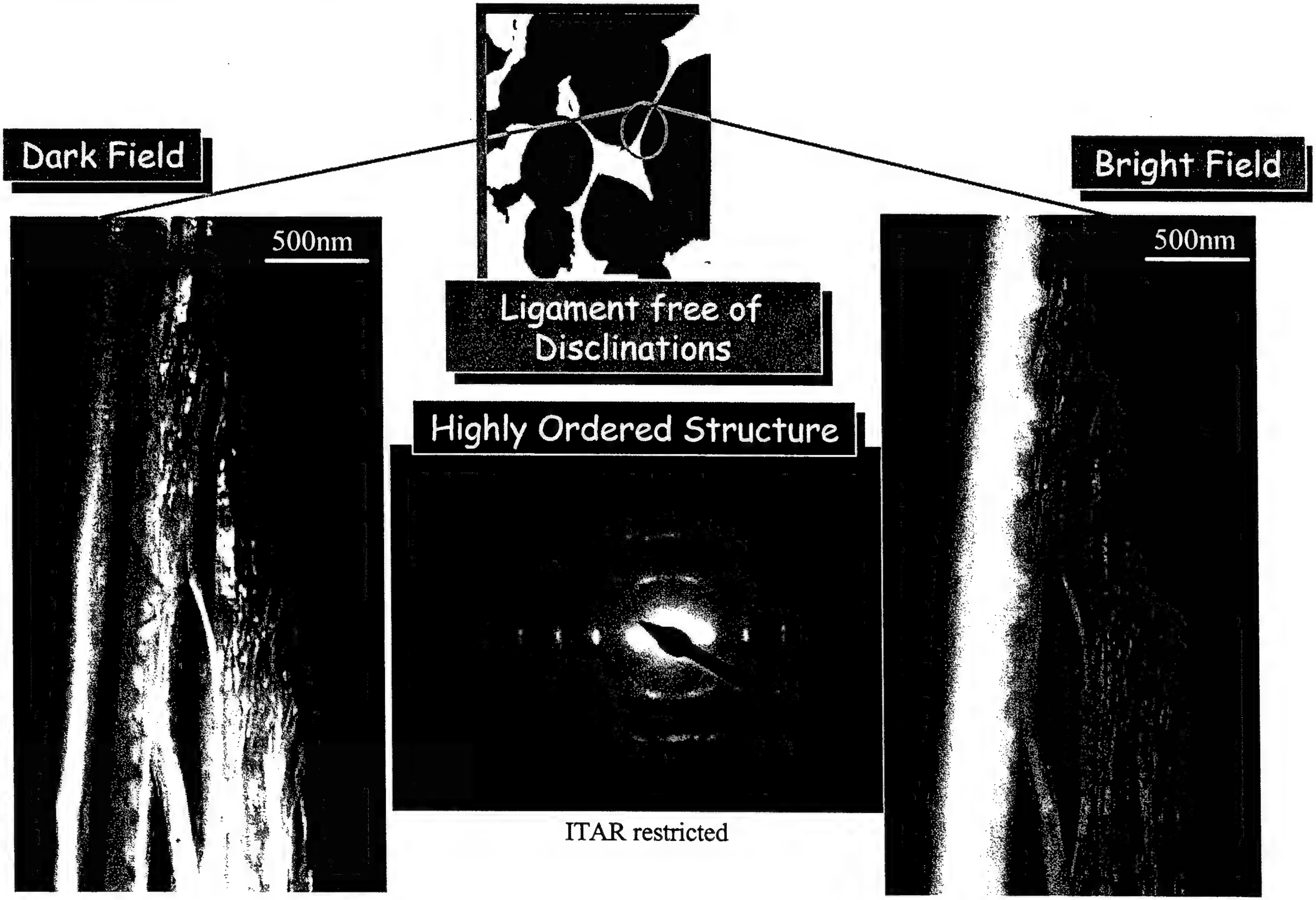




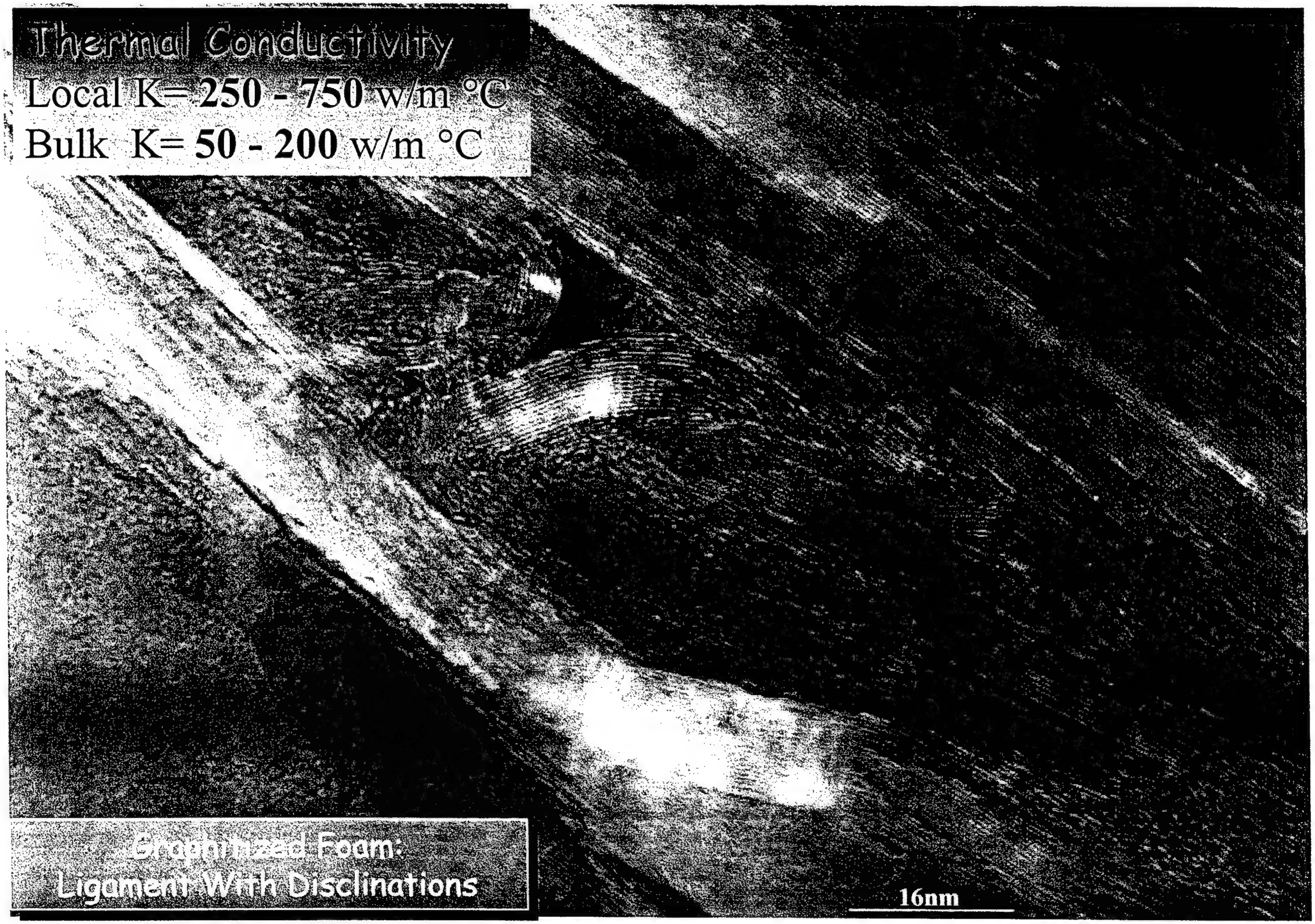


ITAR restricted

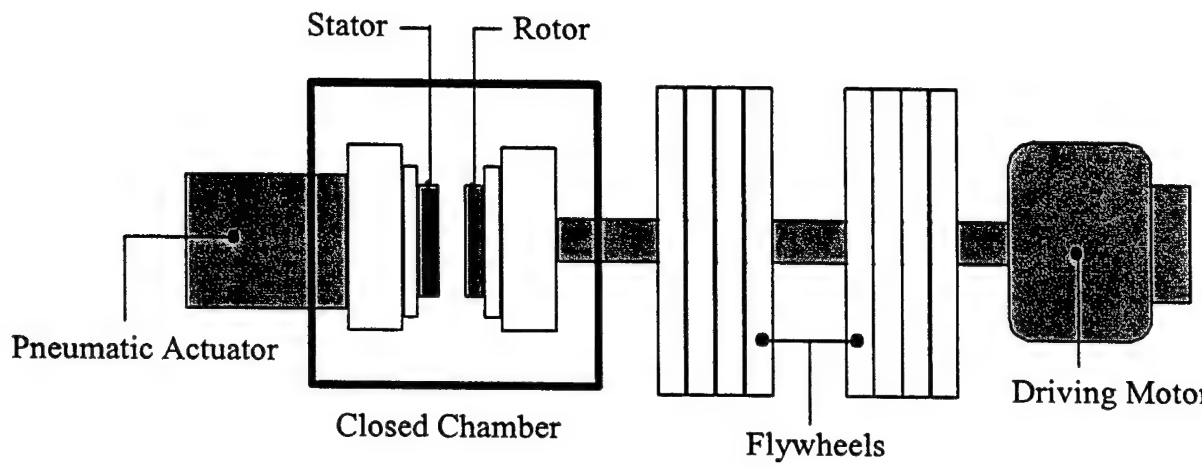
TEM Characterization of Graphitic Foam



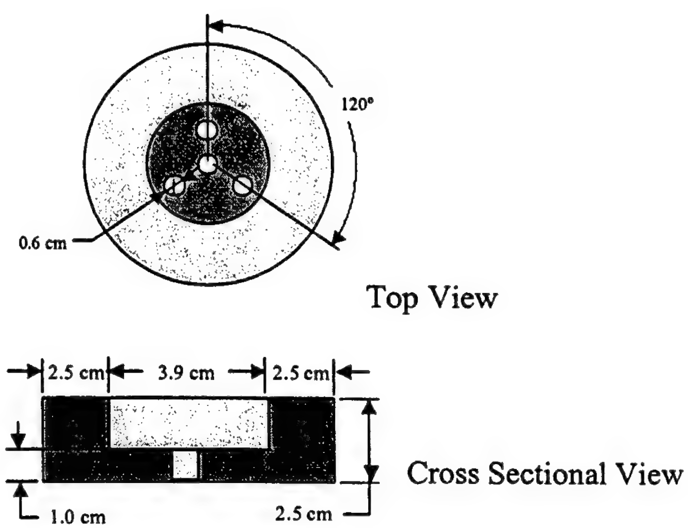
ITAR restricted


Thermal Conductivity
Local K= 250 - 750 w/m °C
Bulk K= 50 - 200 w/m °C
Graphitized Foam:
Ligament With Disclinations
16nm

Testing Conditions Using Sub-Scale Dynamometer



Schematic of the sub-scale dynamometer



Dimensions of C-C composite brakes

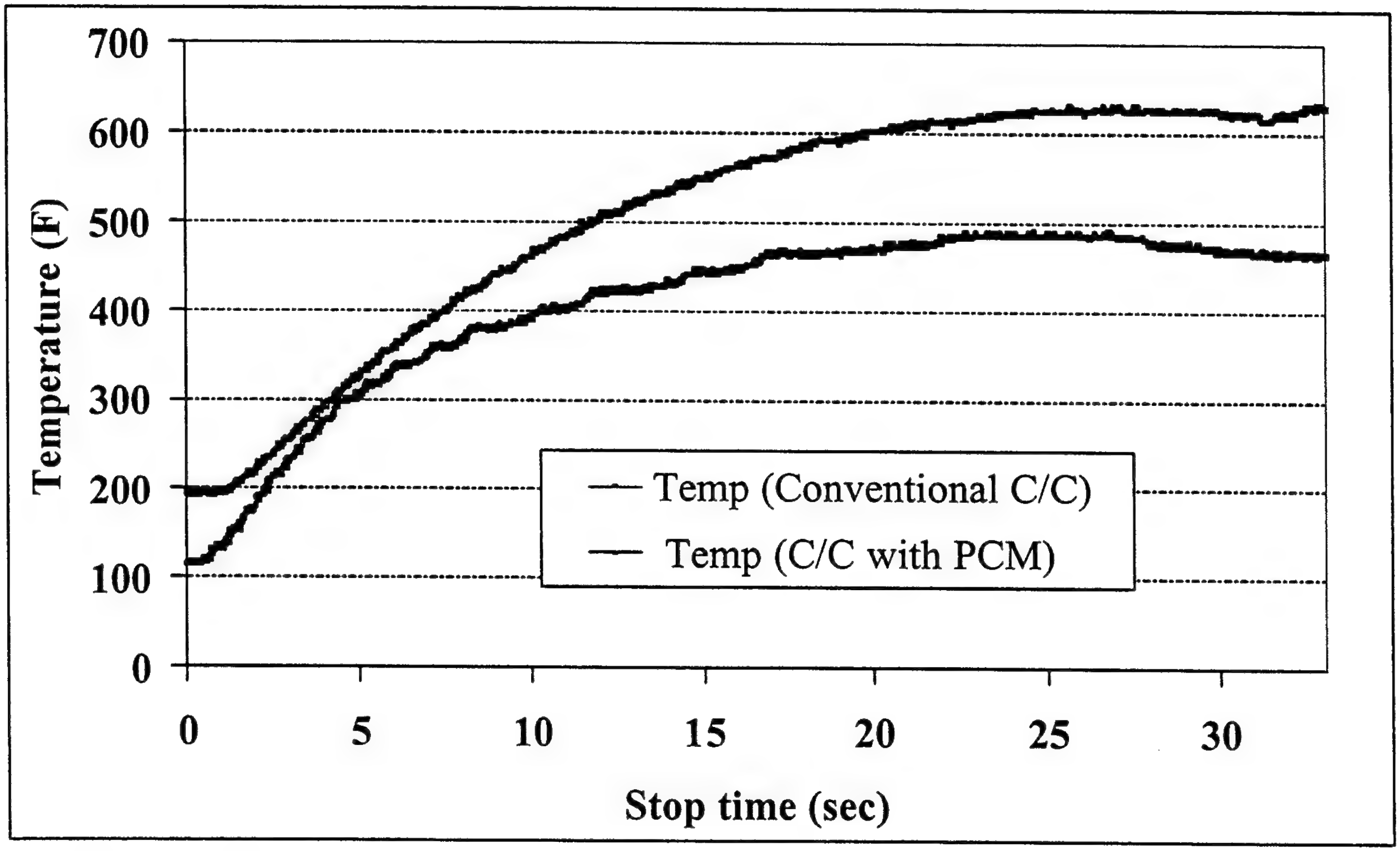
Test	Number of stops
Cold Taxi	100
Service Landing	100
Normal Landing	100
Taxi-Landing	50 (3 L.stps & 1 Taxi. stp)
Rejected take off	5 stops

Testing energy of the sub-scale dynamometer

ITAR restricted

Temperature Profile at Landing condition

The thermocouple was located 5 mm from the sliding surface

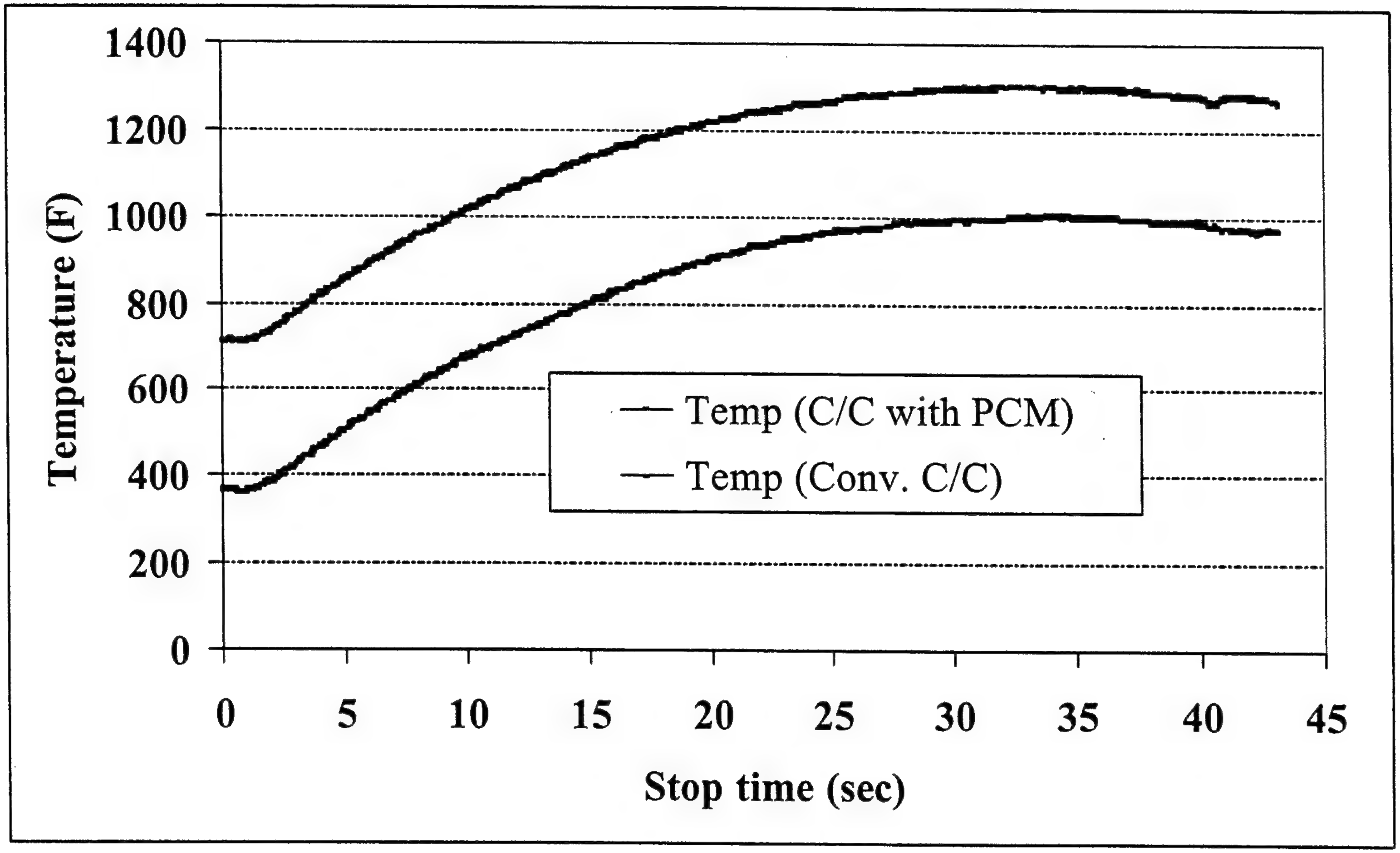


Temperature profile during normal landing Stop of conventional carbon-carbon composites and PCM-graphitic foam based composites.

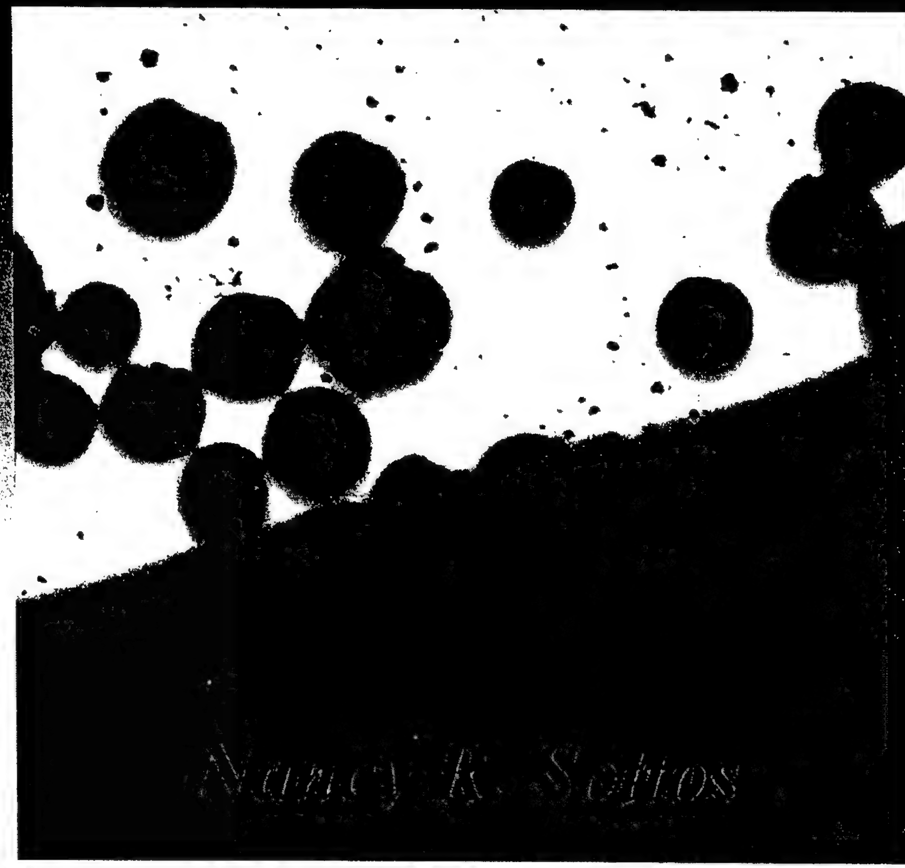
ITAR restricted

Temperature Profile at Rejected Takeoff condition

The thermocouple was located 5 mm from the sliding surface



Autonomic Healing of Polymers and Composites



University of Illinois at Urbana-Champaign

Beckman Institute for Advanced Science and Technology

ILLINOIS

Autonomic Healing Research Team

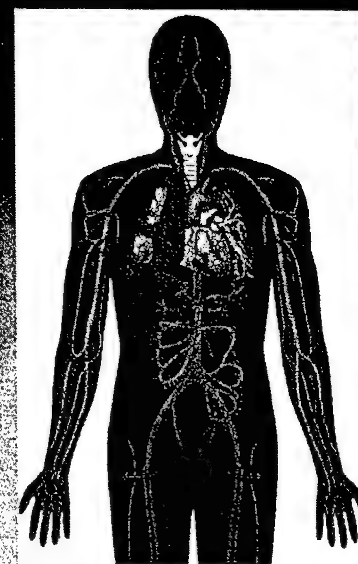
www.autonomic.uiuc.edu

- Faculty: Scott White, Nancy Sottos, Philippe Geubelle, Jeff Moore, Paul Braun, Jennifer Lewis
- Students: Eric Brown, Joe Rule, Daniel Therriault, Jeff Thompson, Mike Kessler*, Suresh Sriram*, Sabarivasan Viswanathan*
- Support: UIUC-CRI
  AFOSR
  Motorola
  Beckman Institute

Inspired by Biological Systems

Autonomy

The ability to function in an independent and automatic fashion



Autonomic or Self-healing Functionality:
The ability to repair damage in an automatic and site specific fashion <u>without</u> manual intervention.

Our Goal?

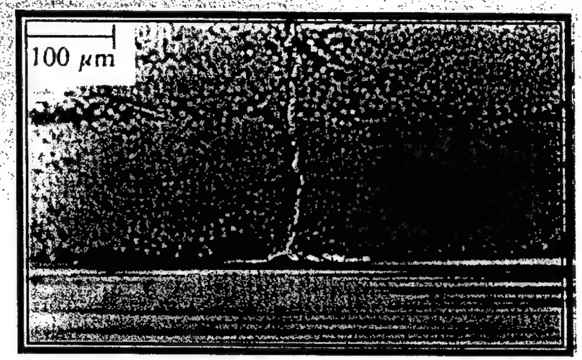
BEFORE

AFTER

Motivation

damage in the form of cracking

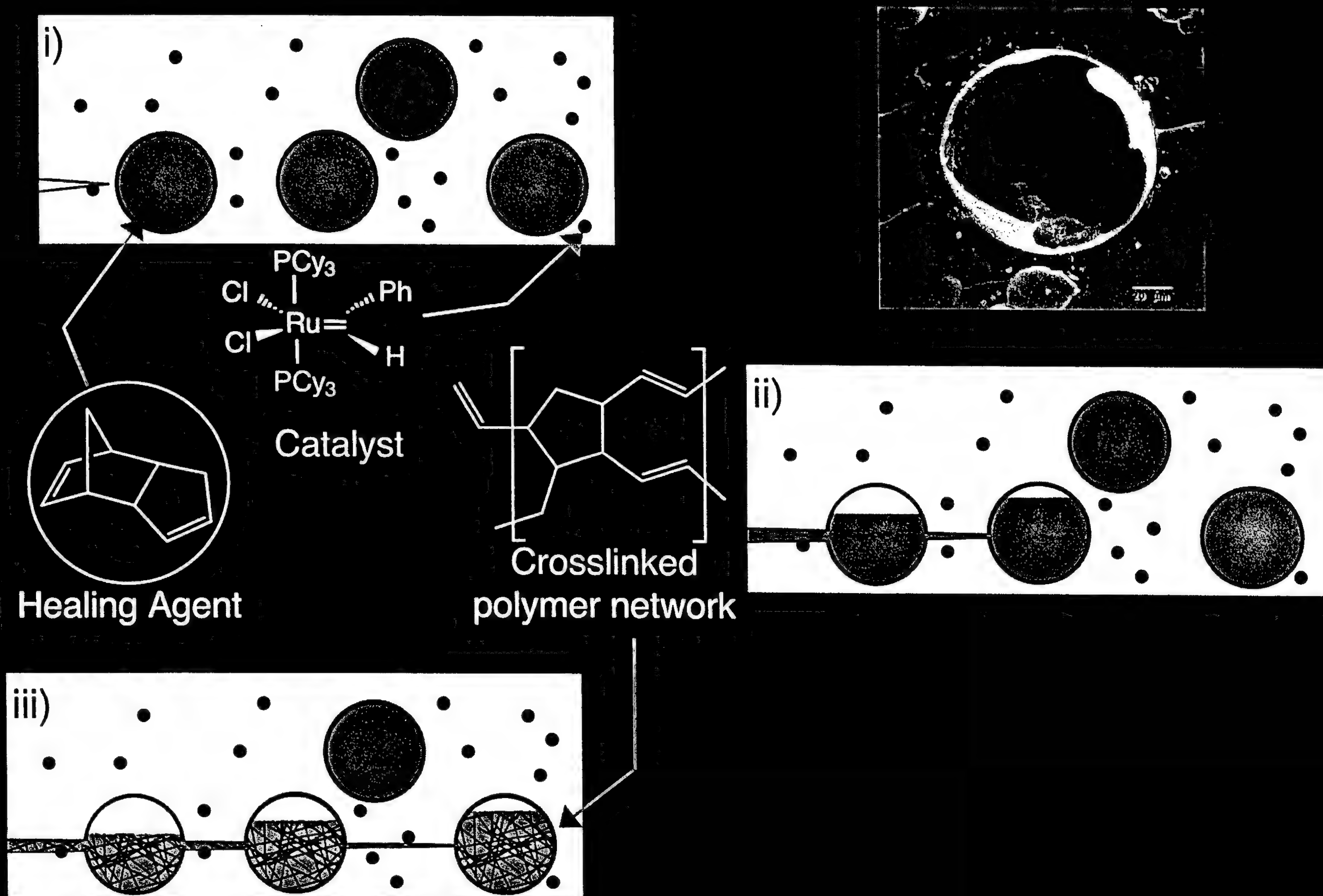
- Structural Composites
  - Matrix Cracking
  - Interfacial debonding
  - Ply delamination
- Microelectronics
  - Interconnect fatigue
  - Polymer encapsulate failure
- Adhesives
  - Microcracking



Cracking in cross-ply laminate
Jennings (1990)

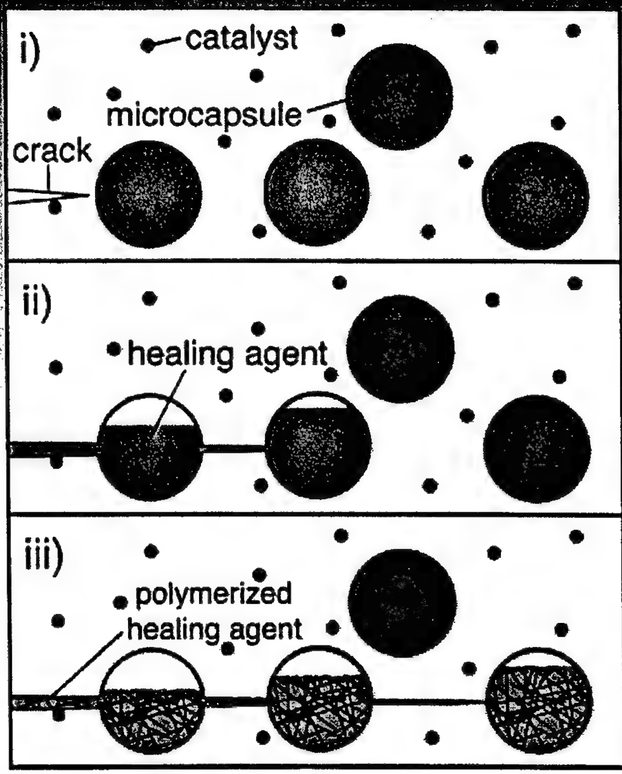
- Cracks are often deep in a structure where detection is costly and difficult
- Repair of cracks by external intervention is often impossible

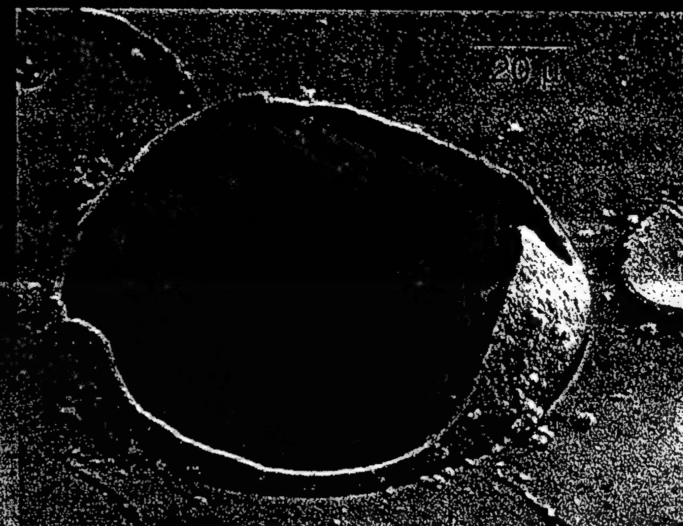
Self-Healing Concept



Self-Healing Materials

Goals:
- 100% recovery of mechanical integrity
- Continuous healing over lifetime
- Seamless integration in material structure

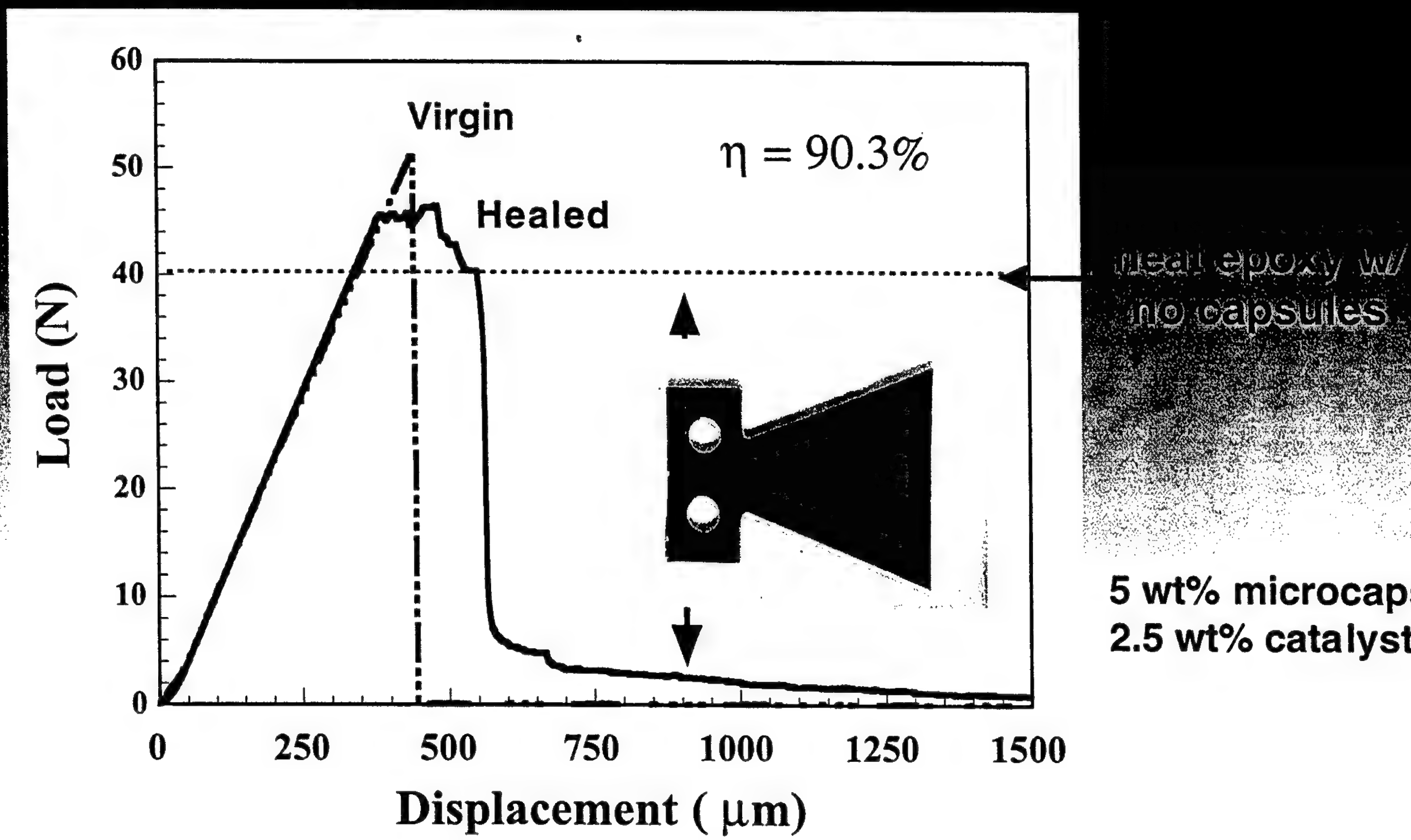




Research Needs:
- Reactive materials development
- Environmental stability
- Mesoscale integration and fabrication
- Multiscale characterization
- Multiscale modeling

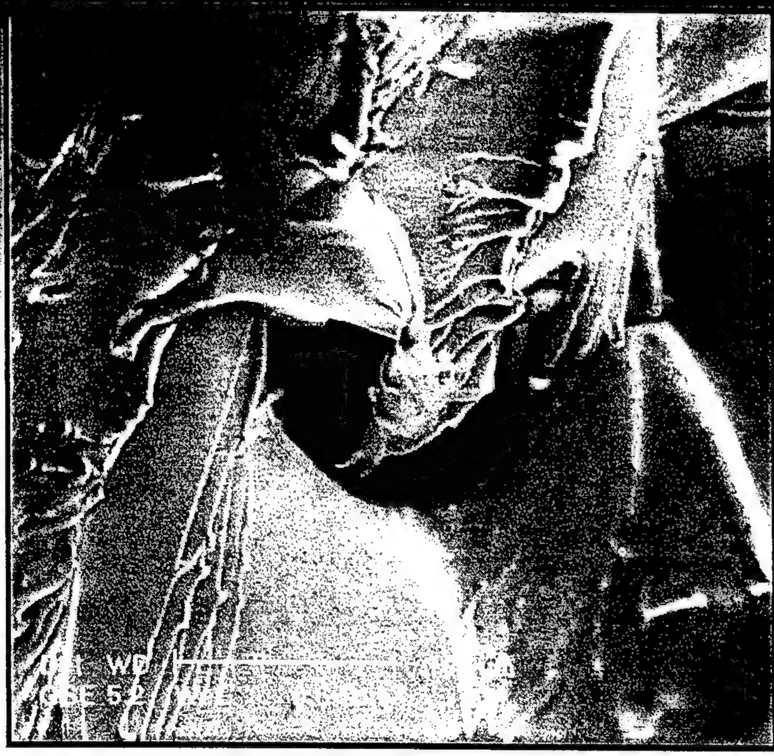
Epoxy Healing Efficiency

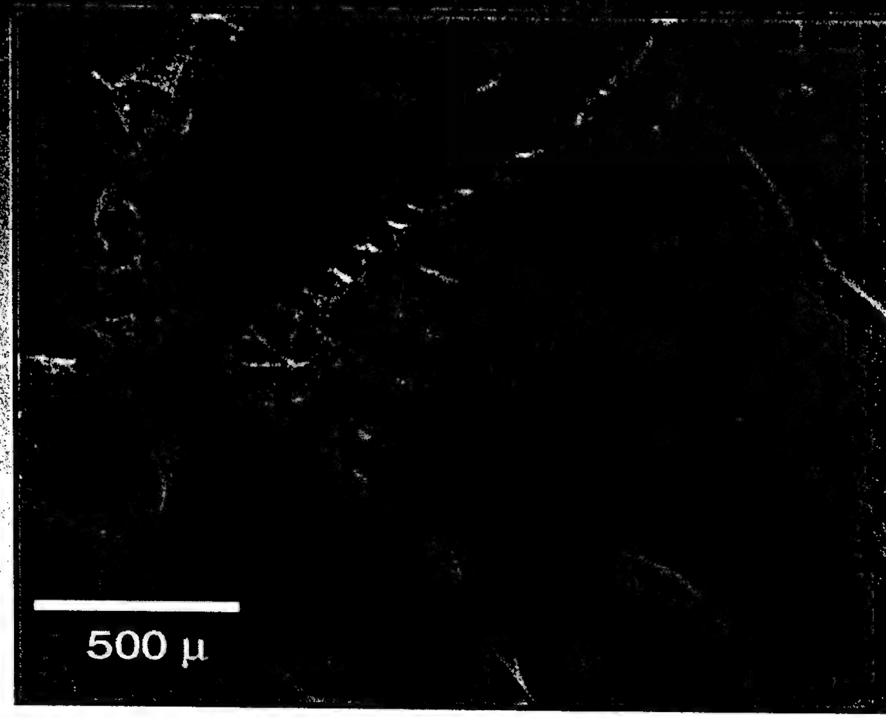
$$\eta = K_{Ic}^{healed} \big/ K_{Ic}^{virgin}$$



5 wt% microcapsules
2.5 wt% catalyst

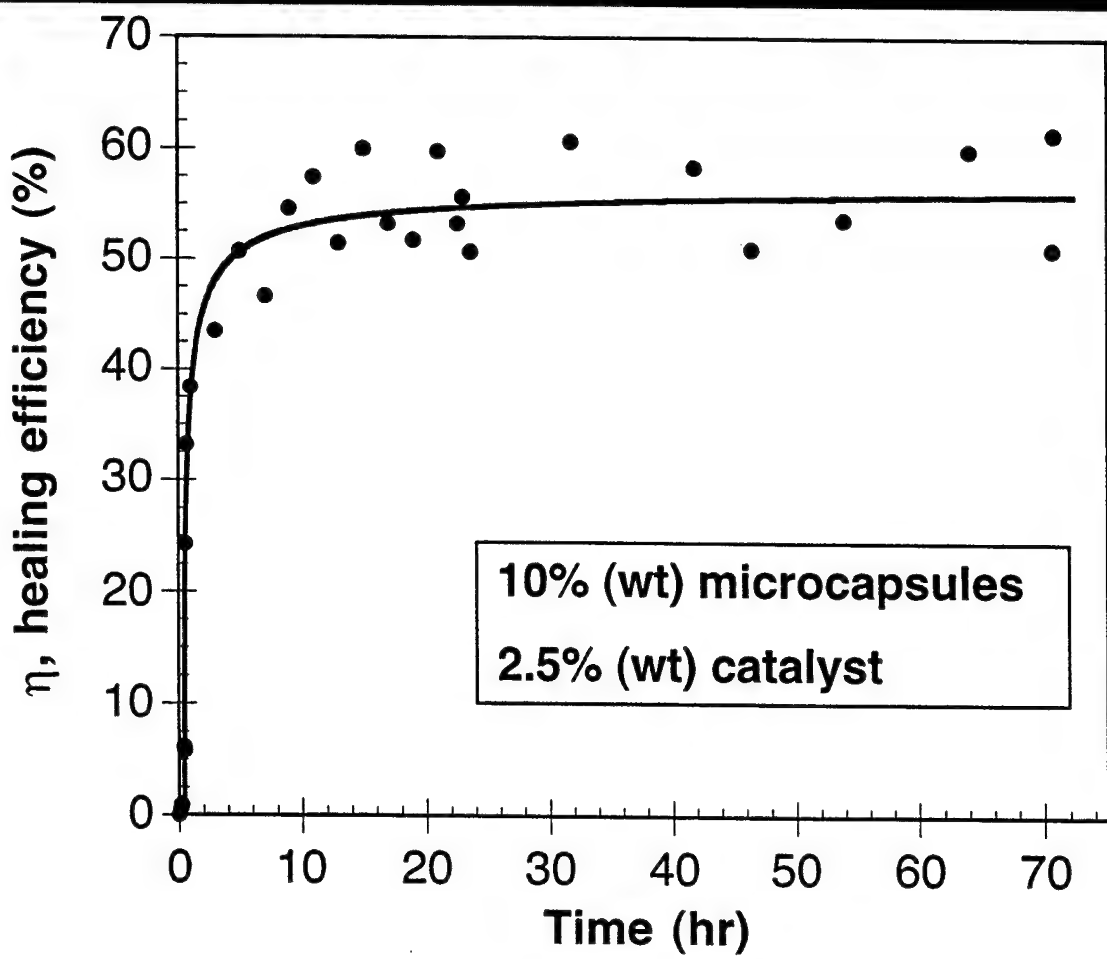
Healed Fracture Surface



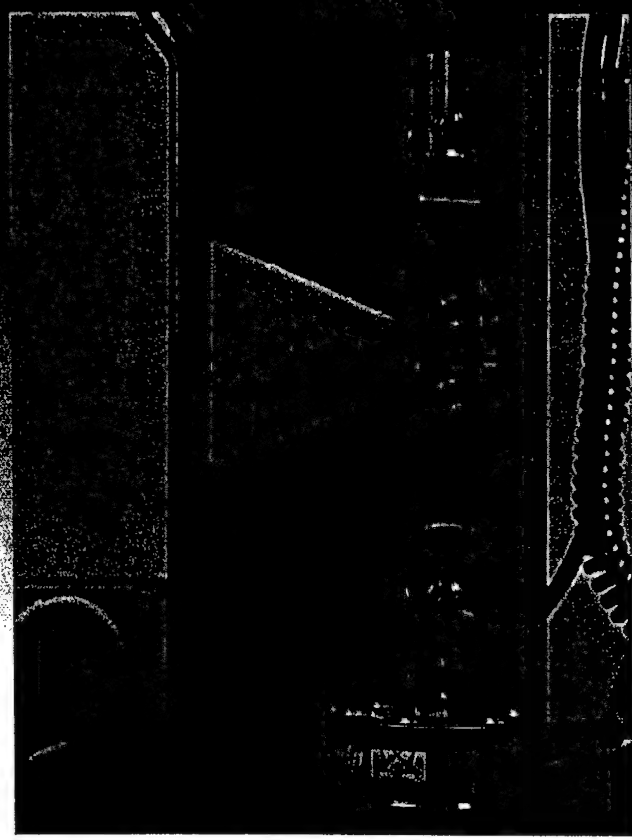


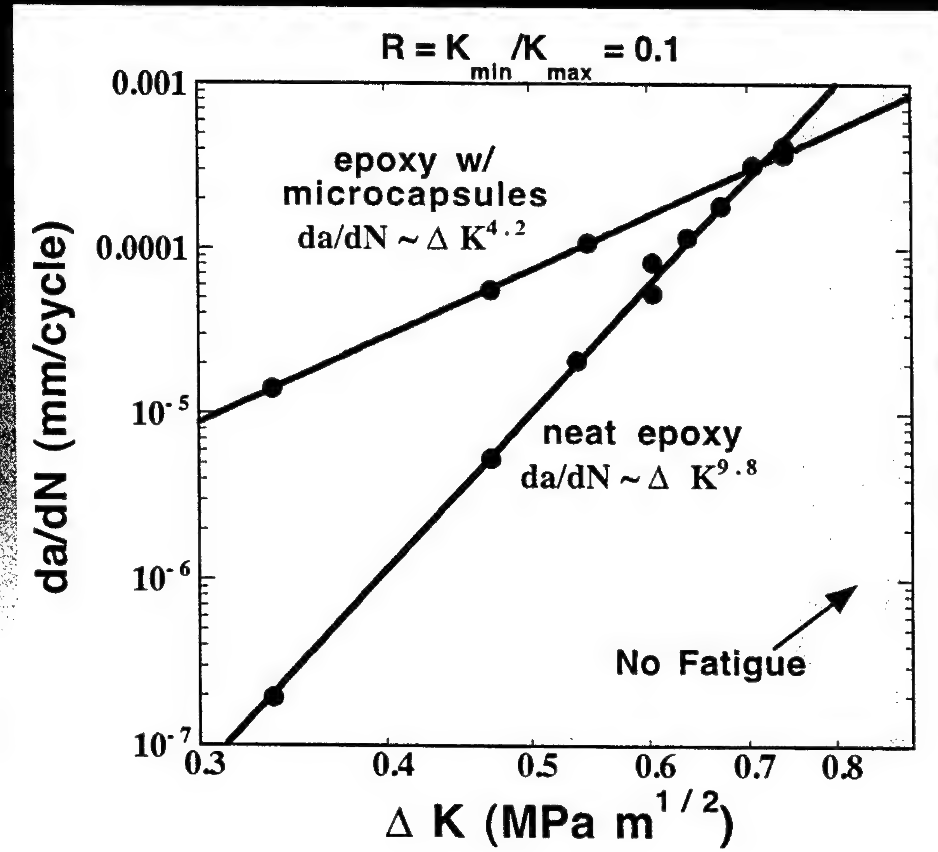
polymerized DCPD film on fracture surface

Healing Kinetics



Healing Fatigue Damage





Multiscale Modeling of Fatigue Response of Self-Healing Composite

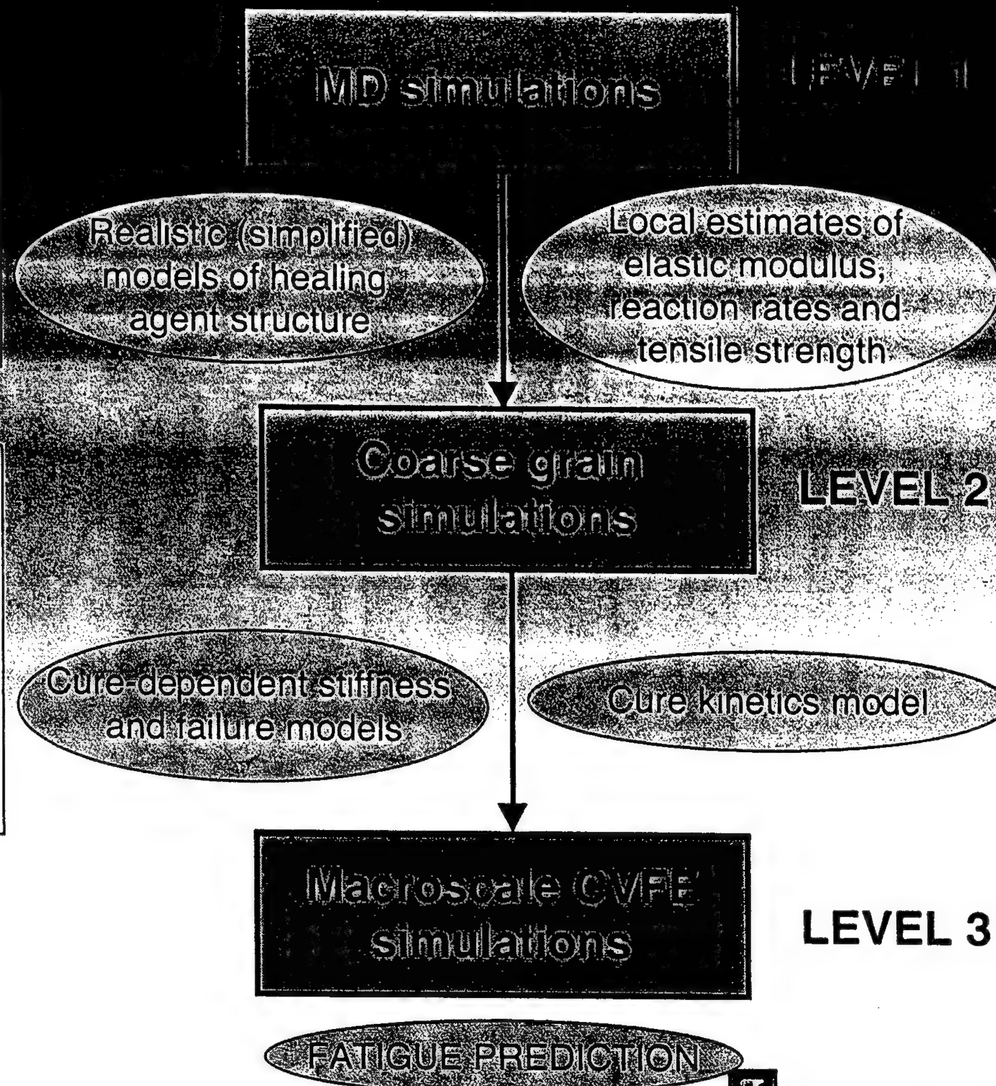
Objective:

Model low and high-cycle fatigue response of autonomic healing in polymeric materials systems

Approach:

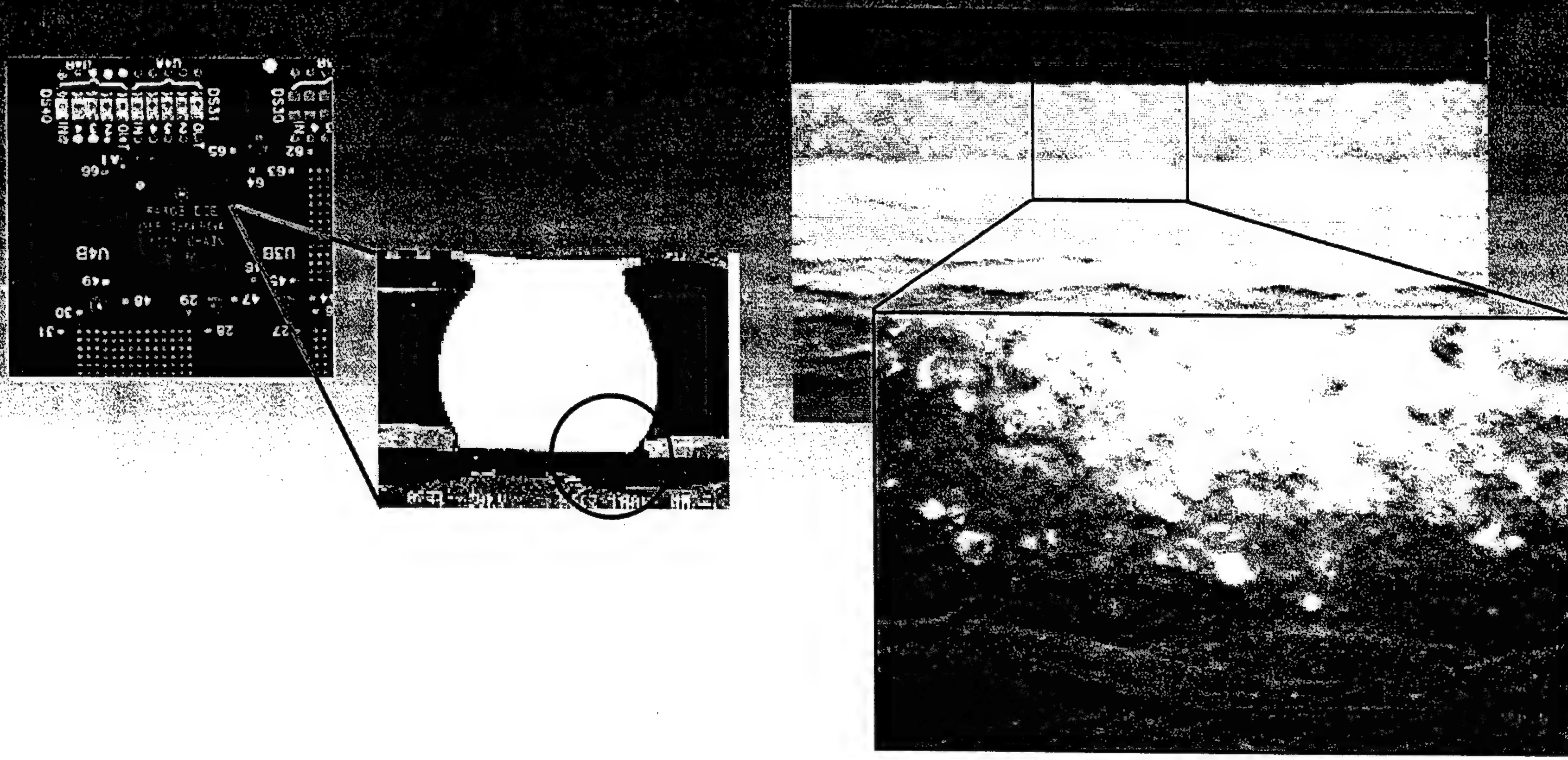
Combination of

- multilevel numerical tools
- multiscale supporting and validating experiments



Tech Transfer: Microelectronics

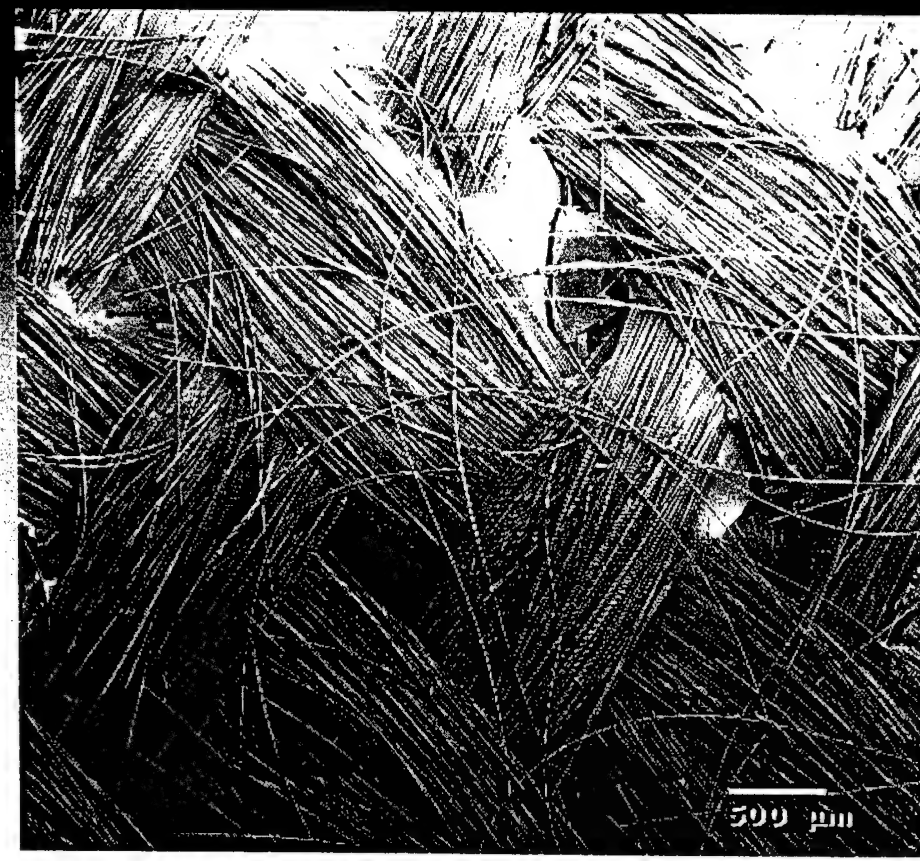
Self-Healing Polymer for Improved Fatigue Life of Microelectronics
Collaborative work with Dr. Andrew Skipor, Motorola Laboratories



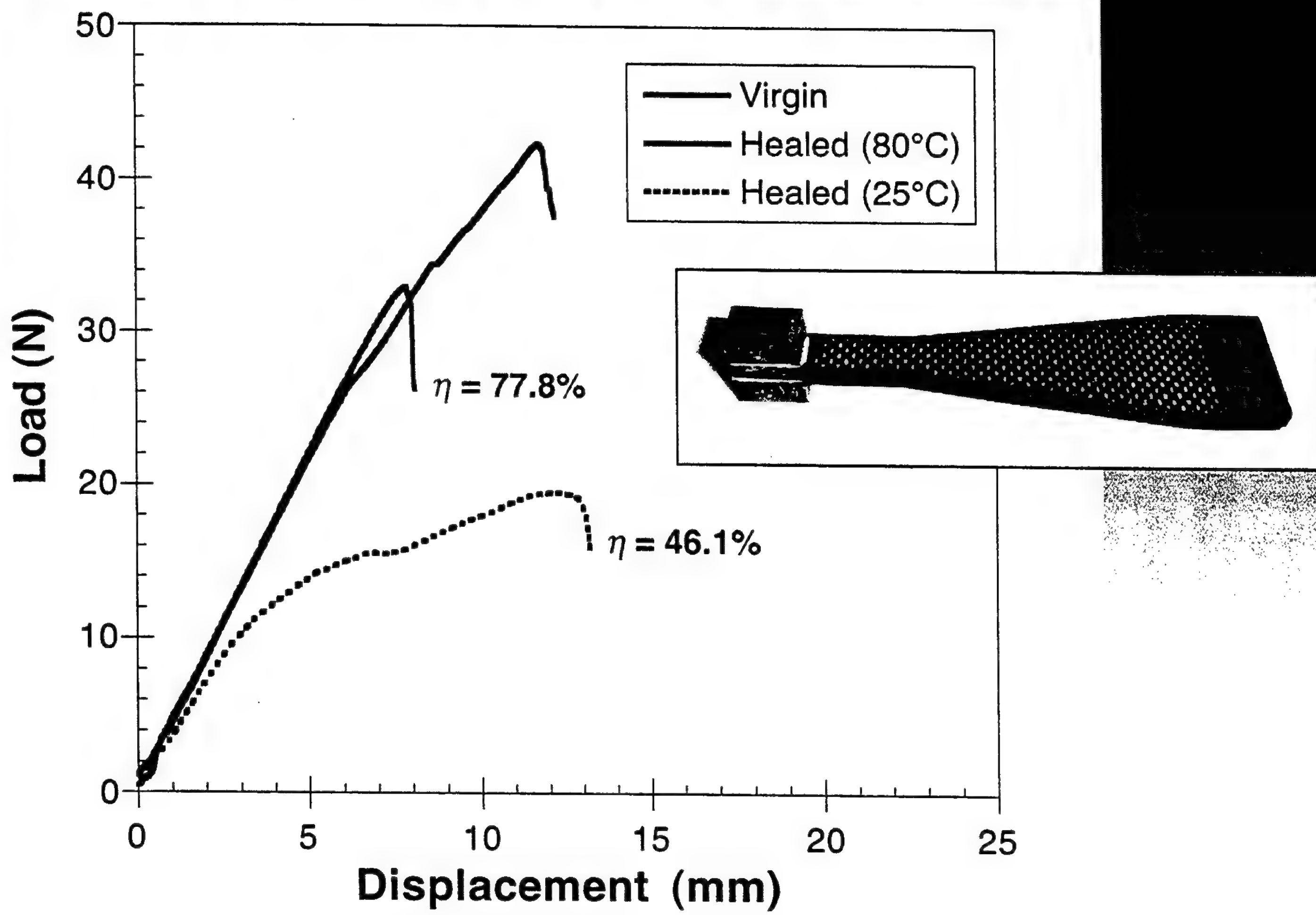
Woven Composites

- interlaminar fracture (delamination) is common:
  - low energy impact
  - manufacturing defect
  - initiate at stress concentrations such as holes and microcracks

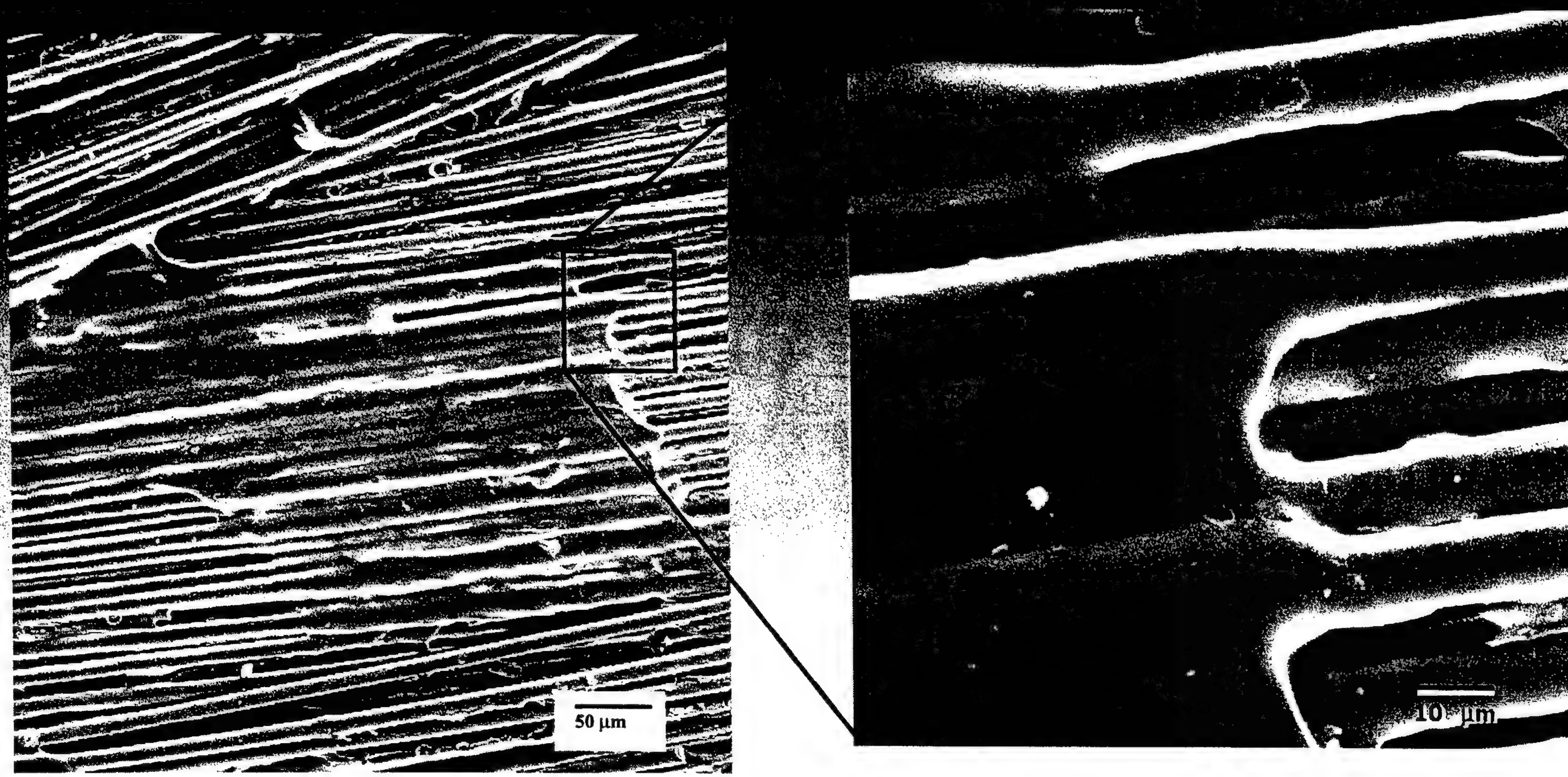
- interstitial areas serve as storage sites for the microcapsules.



Graphite/Epoxy Healing Efficiency



Composite Fracture Surface



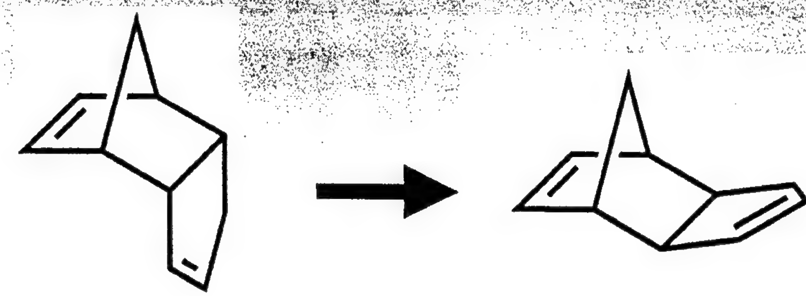
polymerized DCPD

Tech Transfer: Cryogenic Storage Tanks

AFRL/VS STTR "Composite Materials for Cryogenic Storage Tanks and Superconductivity Applications"

- Lead by CU Aerospace, LLC (founded 1995)
- UIUC subcontract
- POC: Captain Brandon Arritt, Kirtland AFB

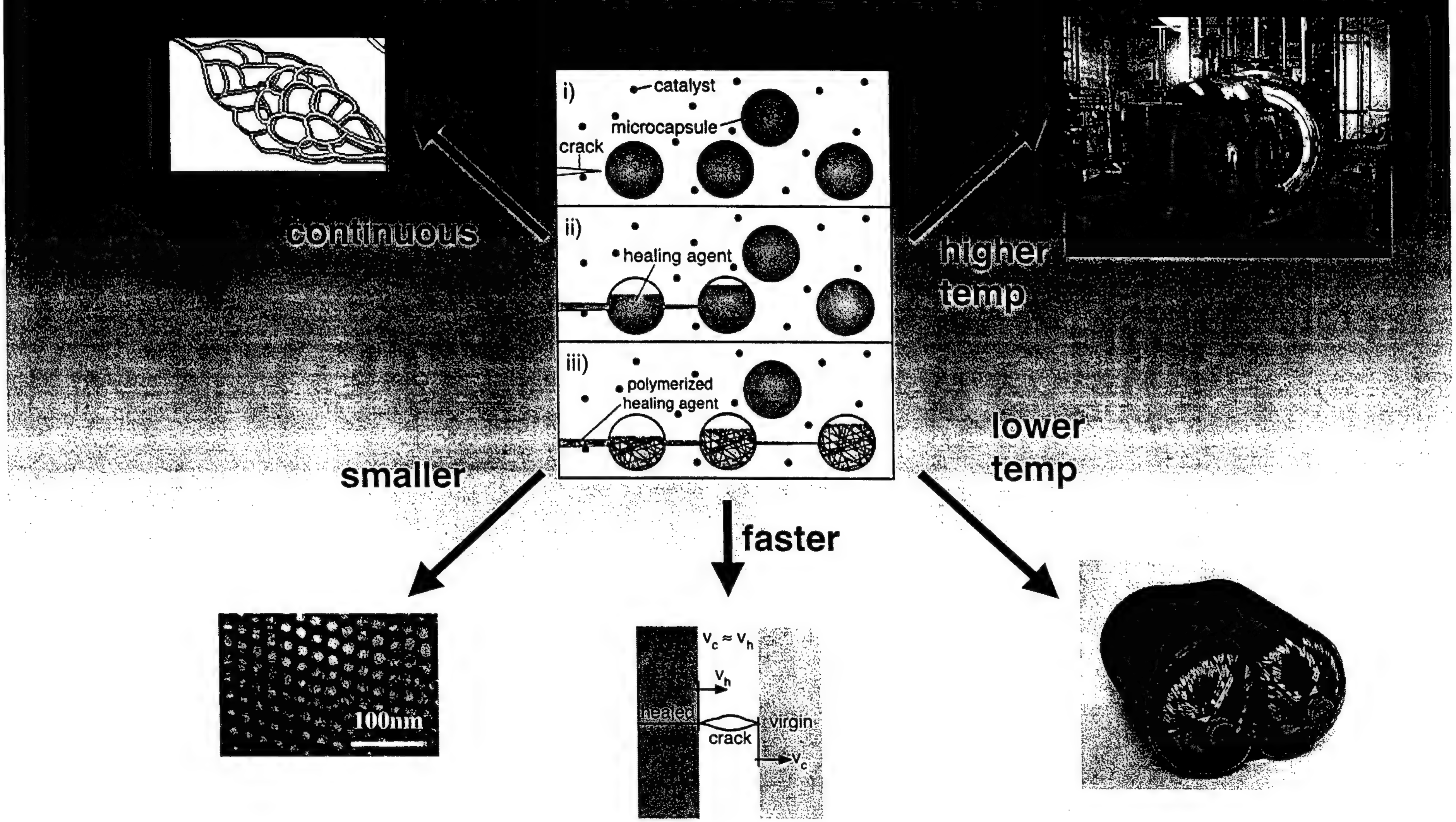
New Healing Agent:



endo - DCPD

exo - DCPD

Future Directions

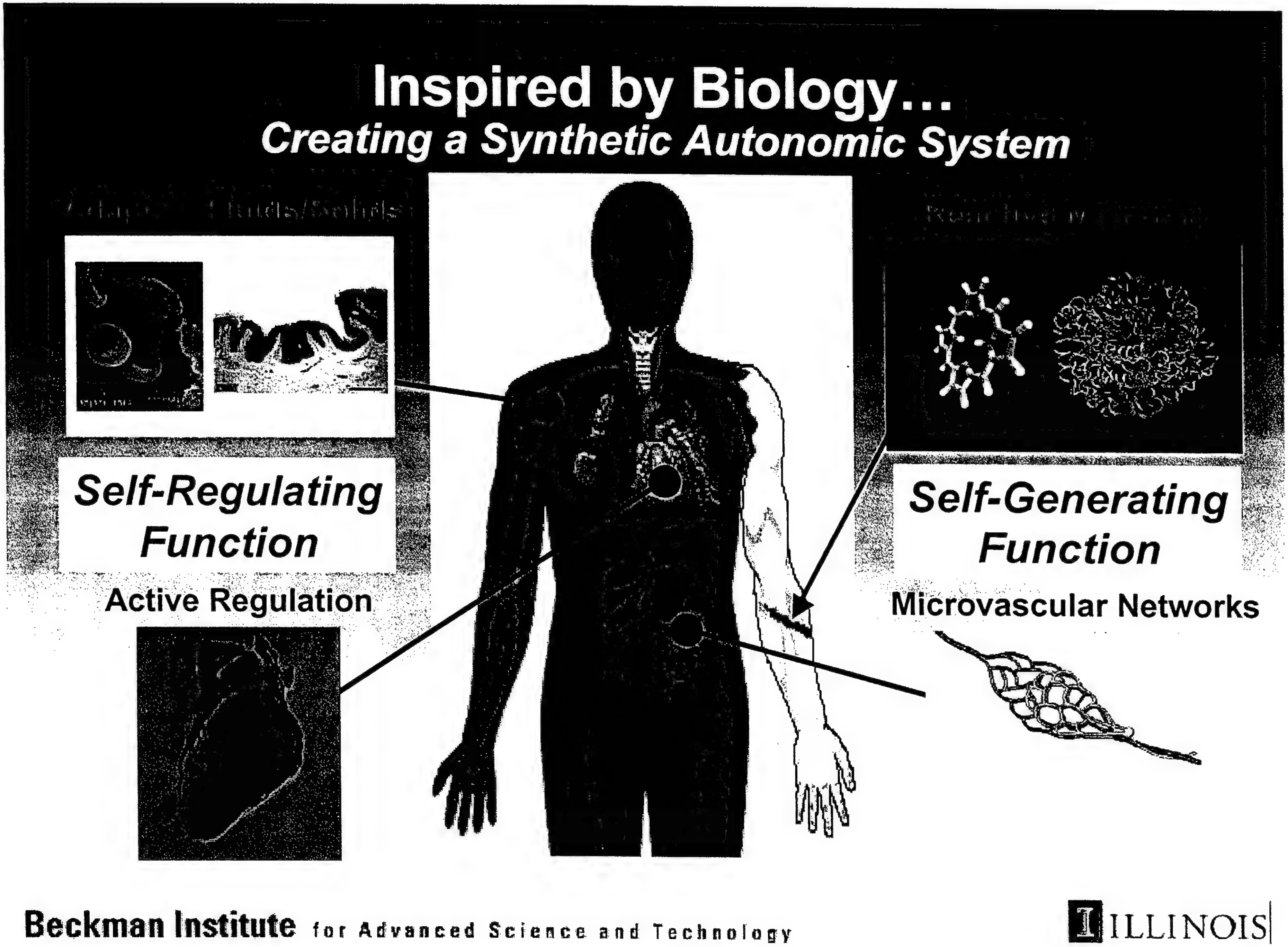


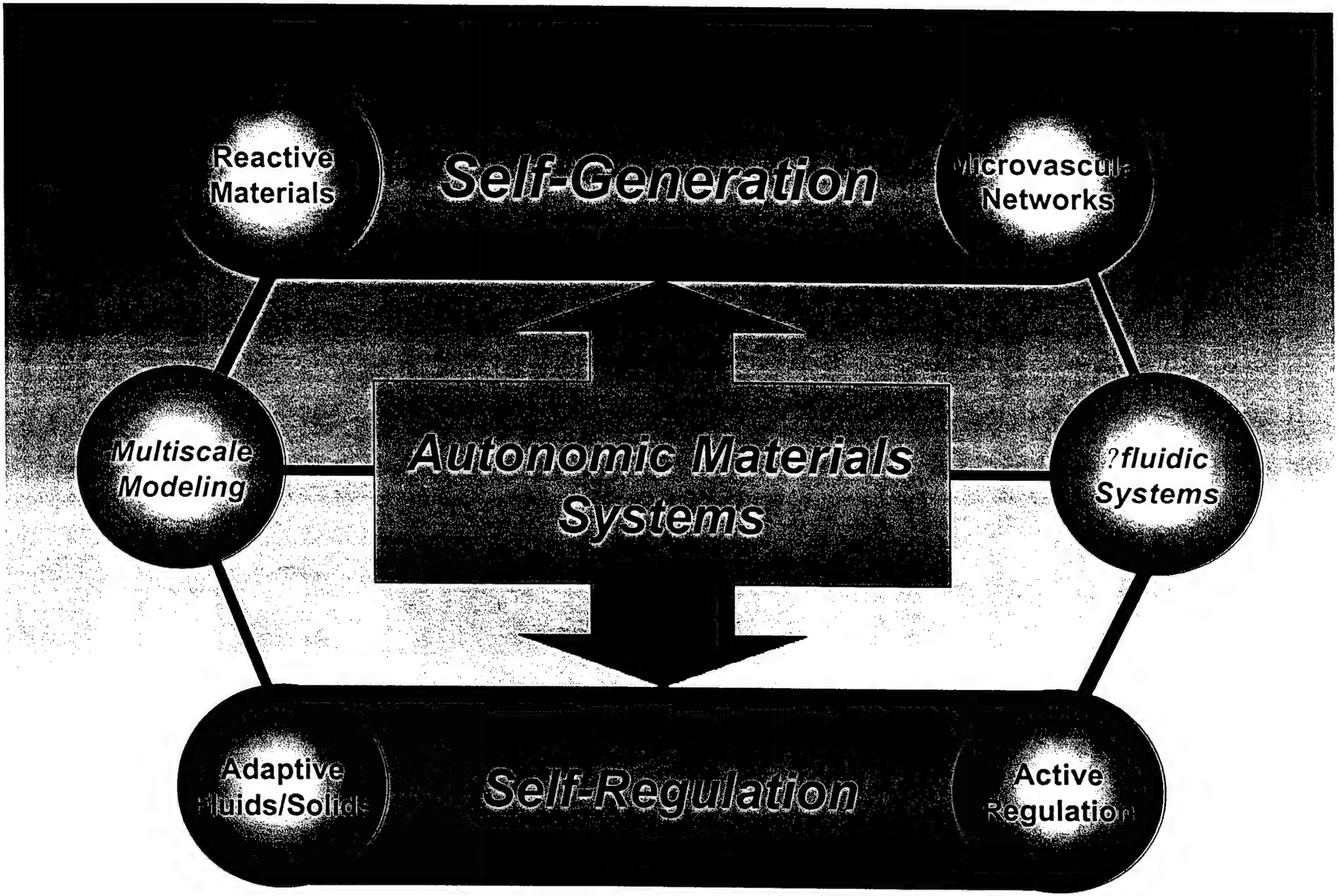
Next Generation Self-Healing

Scott White
University of Illinois at Urbana-Champaign

1st Air Force Workshop on “Multifunctional Aerospace Materials”

Oct. 23-24, 2002..............................Purdue University


Inspired by Biology…
Creating a Synthetic Autonomic System
Self-Regulating Function
Active Regulation
Self-Generating Function
Microvascular Networks
Beckman Institute for Advanced Science and Technology
ILLINOIS


Reactive Materials
Self-Generation
Networks
Multiscale Modeling
Autonomic Materials Systems
?fluidic Systems
Adaptive
Self-Regulation
Active

Current Limitations

- Relatively slow healing (@ reasonable temperatures & catalyst concentrations)
- Catalyst cost, stability @ high temp, exposure to O_2
- No ability to replenish healing agent

New Healing Concepts

- ROMP and ROP based approaches
  - Cyclic esters, carbonates, ...
- Mechanochemistry approaches
- Microvascular Networks

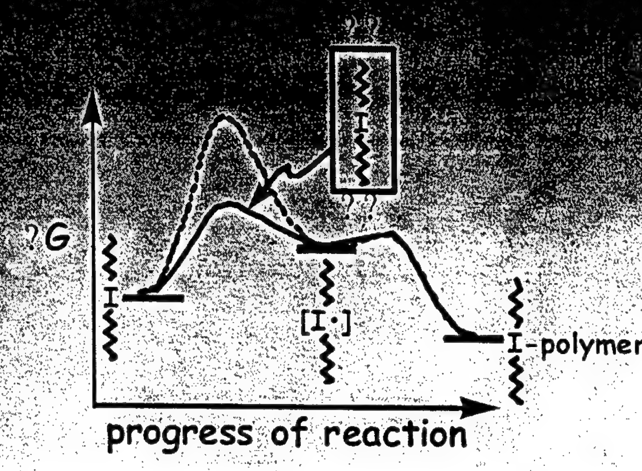
Mechanochemistry:

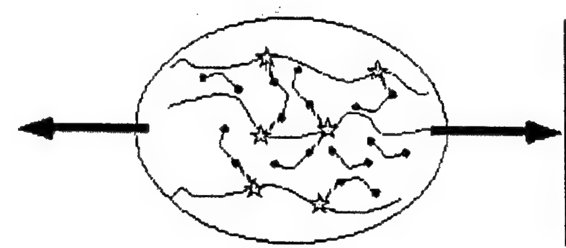
Stress-Activated Schemes

- Application of a stress field lowers energy barrier to reactive state

- Radical generation is coupled directly (and tailored?) to mechanical field

- Candidate molecules have been identified that undergo *Bergman cyclization* to test concept





Mechanochemistry:

Fracture Triggered Polymerization

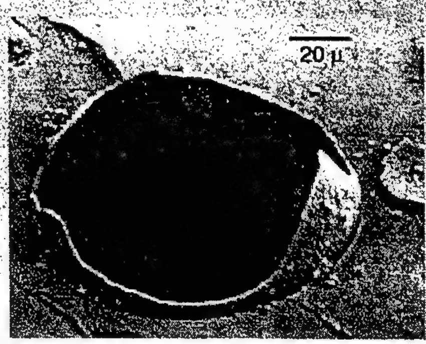
Develop "catalyst-free" systems utilizing the radicals generated on freshly fractured surfaces

ISSUES:

- Radical turnover (amplification) by catalytic chain transfer processes
- Radical trapping (radical acceptors have been identified)
- Can we deliver monomer before secondary events (radical recombination, quenching,...) take place?

Microvascular Networks

Compartmentalization to Circulation

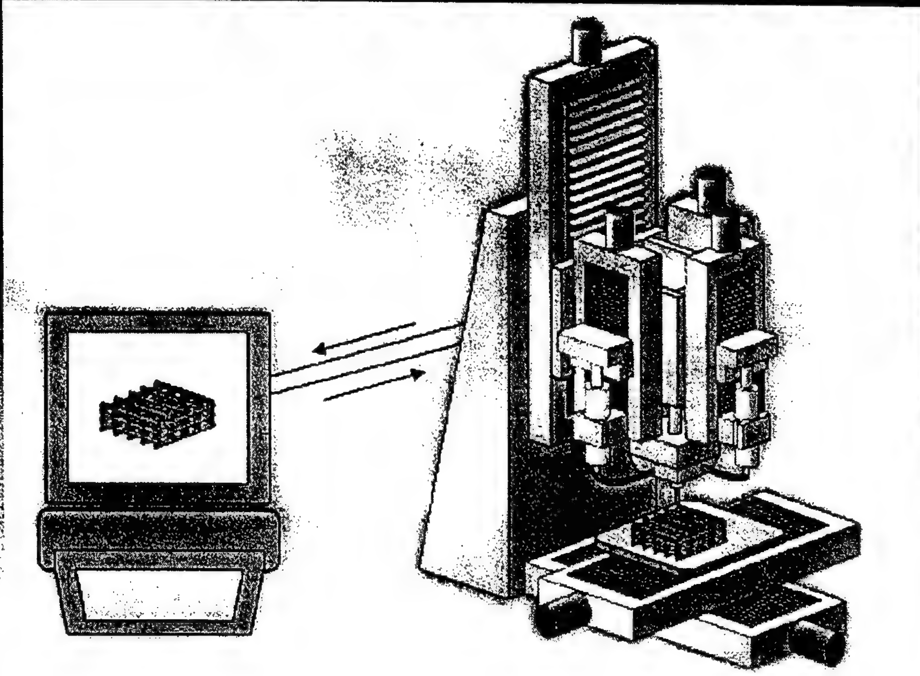


QuickTime™ and a
H.263 decompressor
are needed to see this picture.

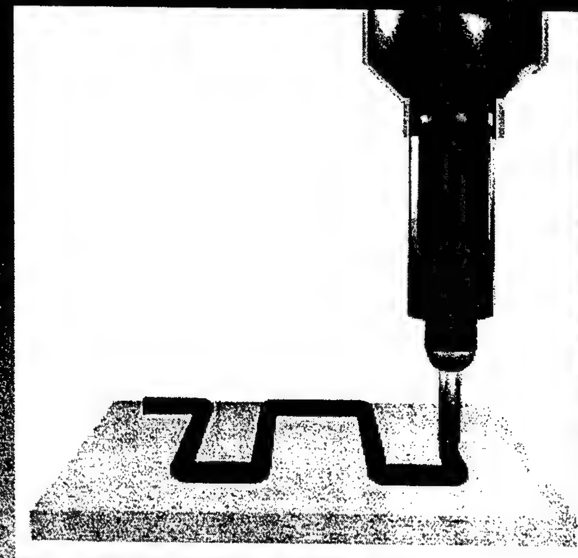
Microvascular Networks

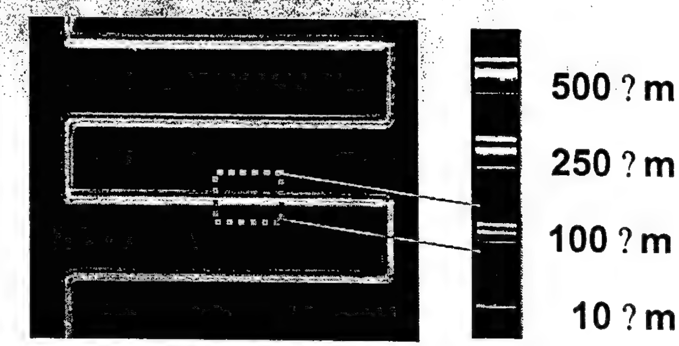
- Hierarchical circulatory networks in biological systems
- Key feature at the microscale is pervasive and interconnected system of microchannels

Microvascular Network Fabrication

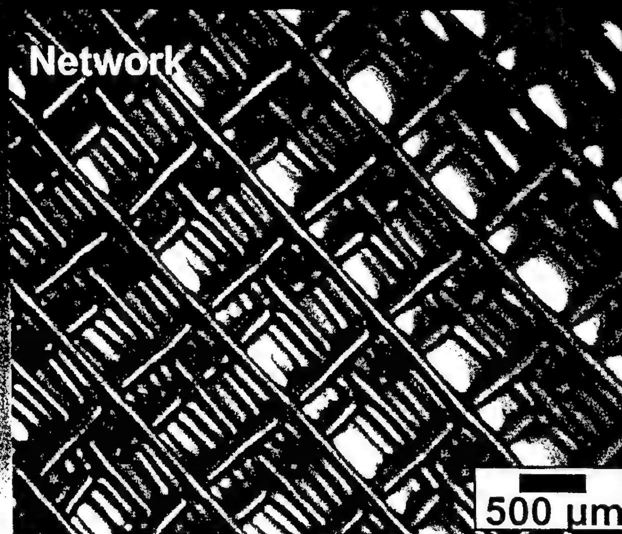


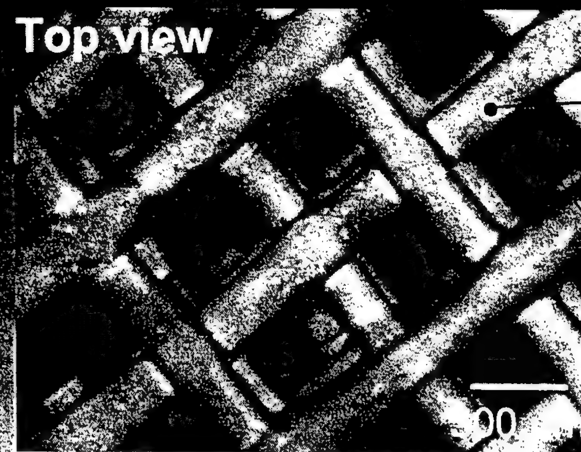
Robotically controlled deposition (RCD) machine

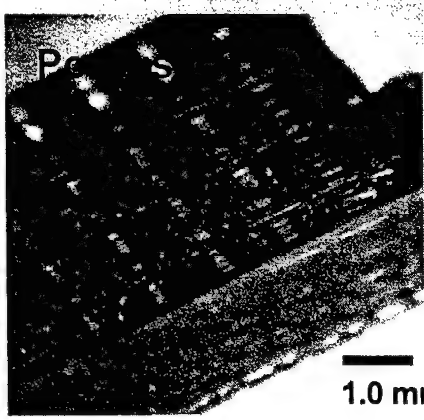


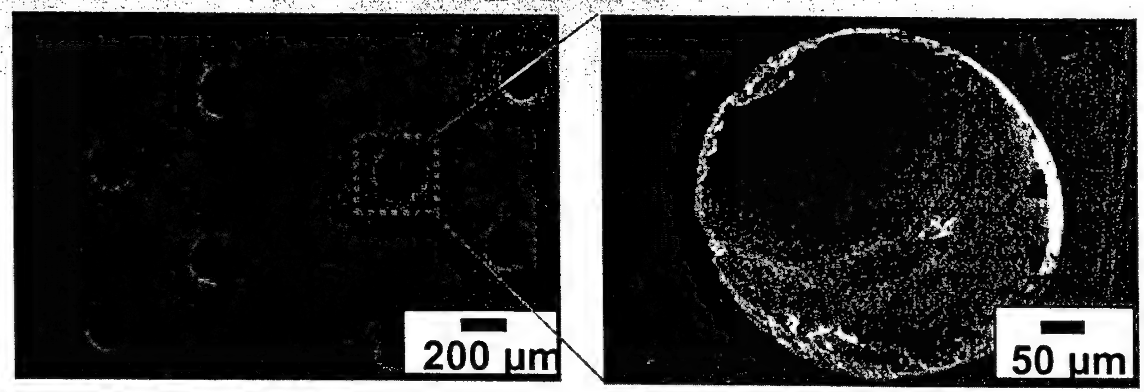


3-D Microvascular Networks

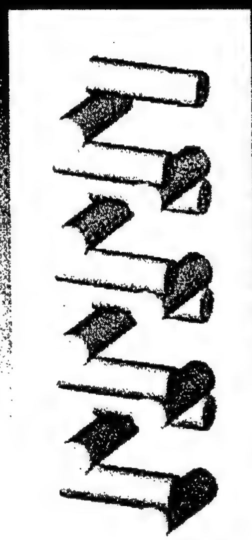


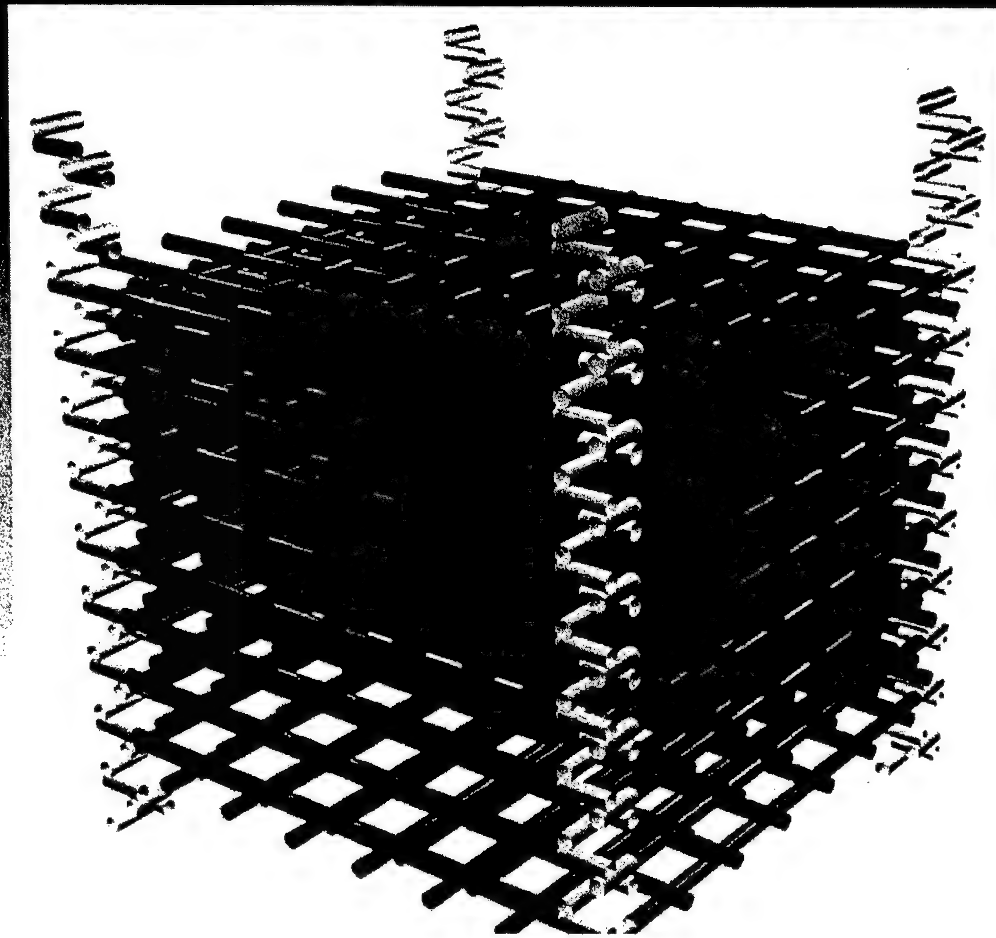


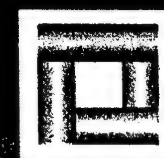




Chaotic Advection Micromixer

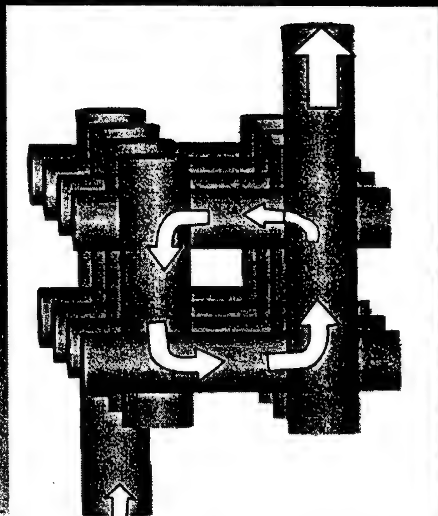




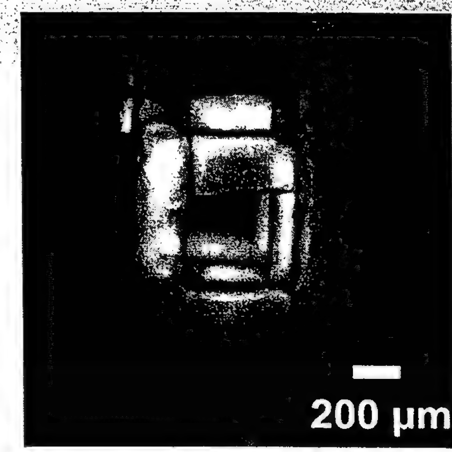


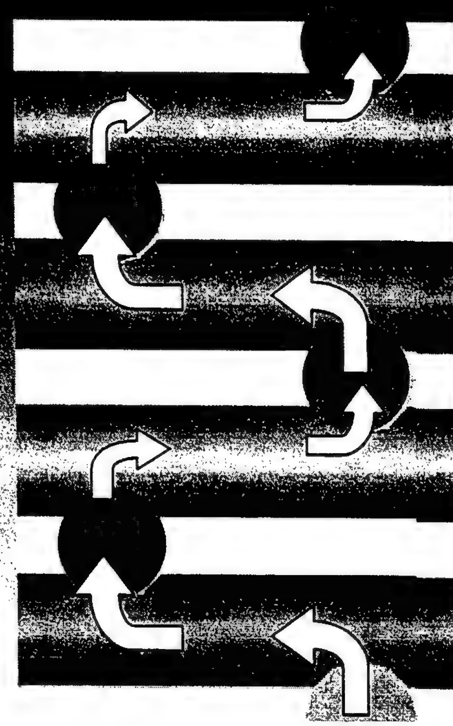
Side view

Isolated Flow Paths



Top view

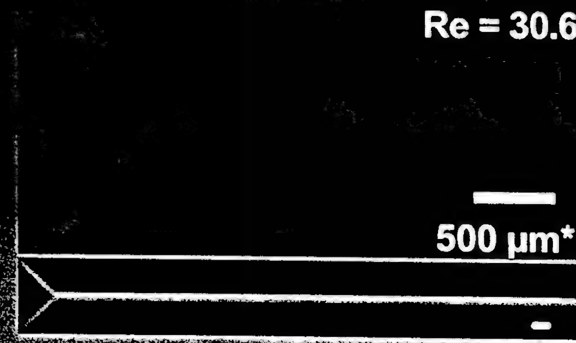




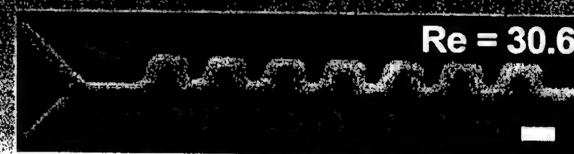
Side view

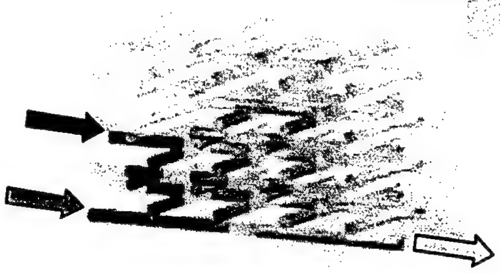
Micromixing Experiments

Straight channel (1-D)

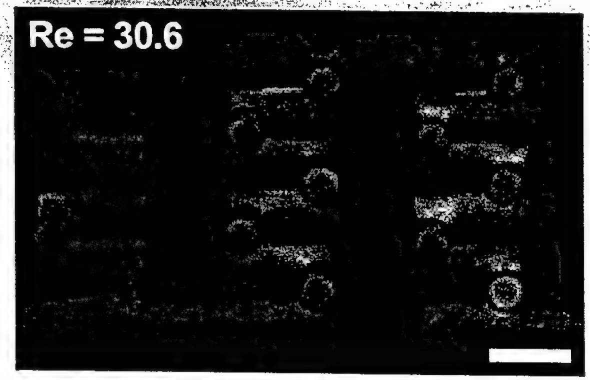


Square wave channel (2-D)





Series of mixing towers (3-D)



*: all scale bars are 500 ? m.

A Challenge for Mechanics...

- Multifunctionality can be (and perhaps should be) led by the mechanics community!
- This is an opportunity as a community to step to the forefront and lead the next generation of materials developments.
- We MUST reach out to other disciplines and facilitate collaborative research from the ground up.

→ We're talking about new materials, not bonding old ones together.

Thermally Re-mendable Cross-linked Polymeric Materials

Xiangxu Chen

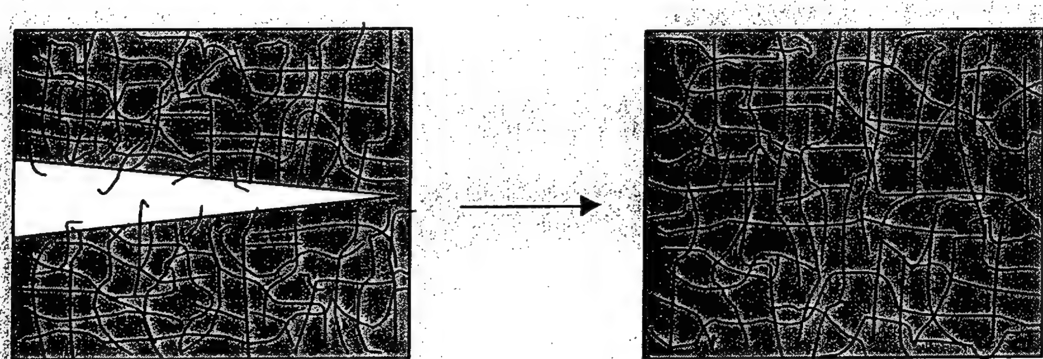
Exotic Materials Institute
Department of Chemistry & Biochemistry
University of California, Los Angeles

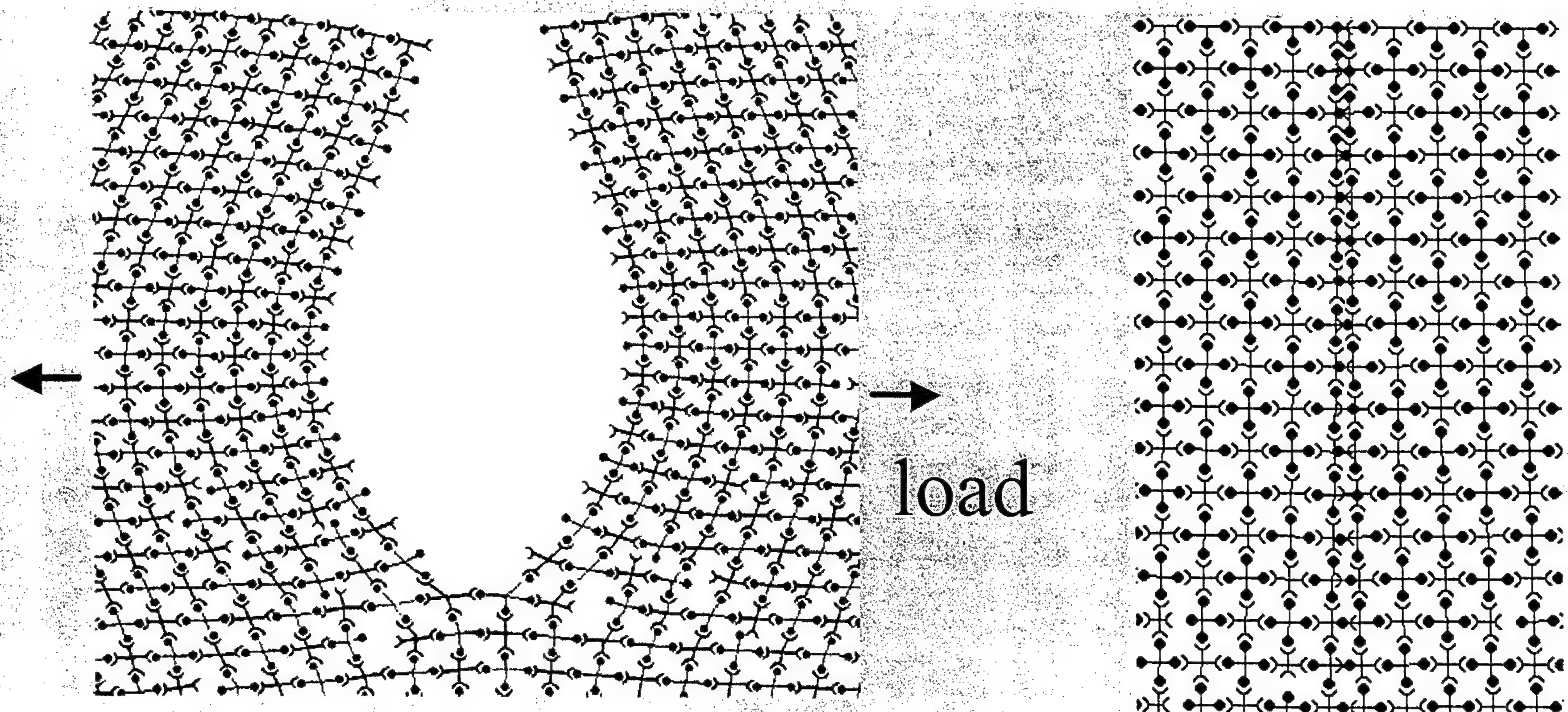
Polymeric Materials

Molecules

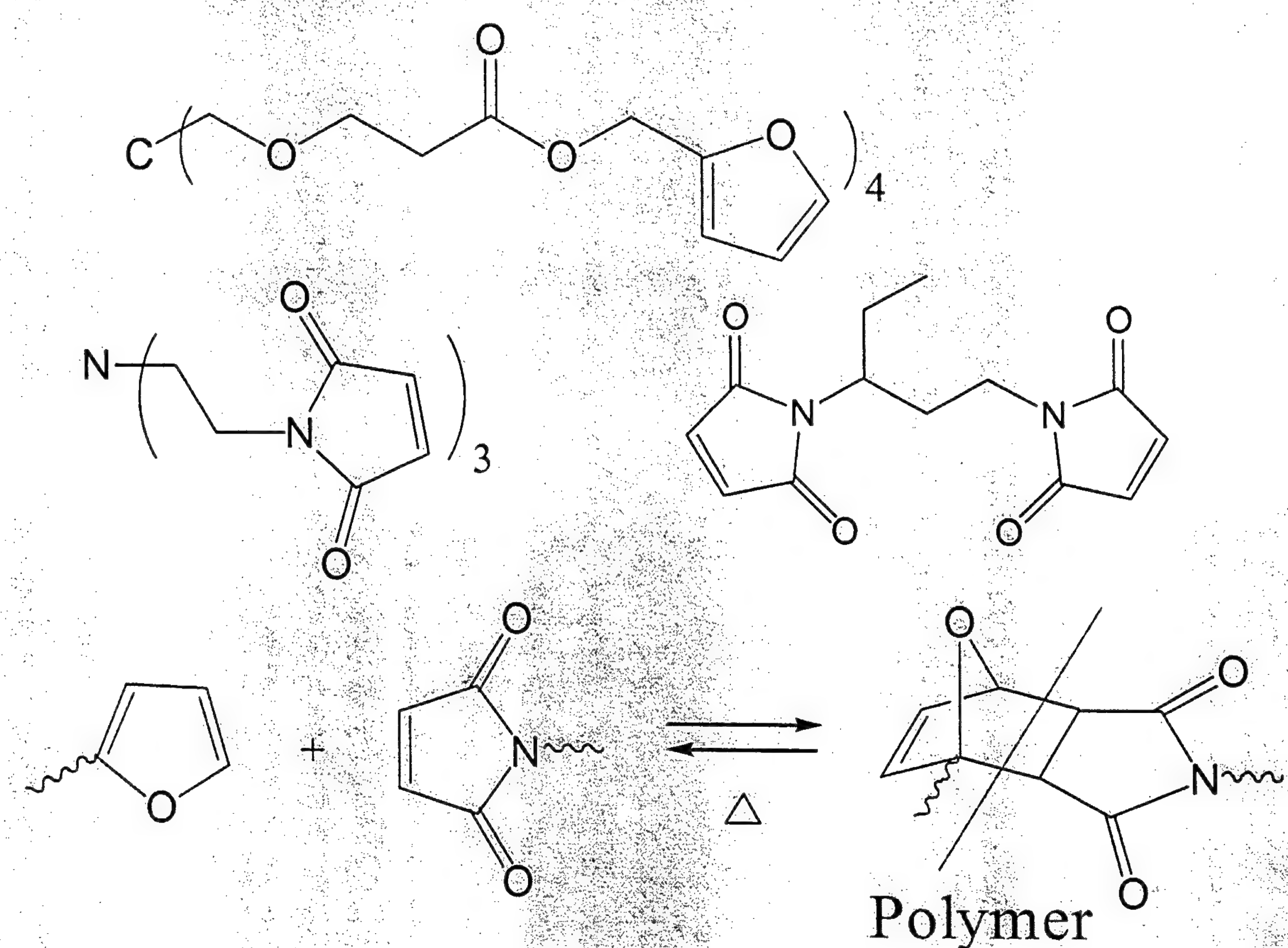
Chemical Bonds

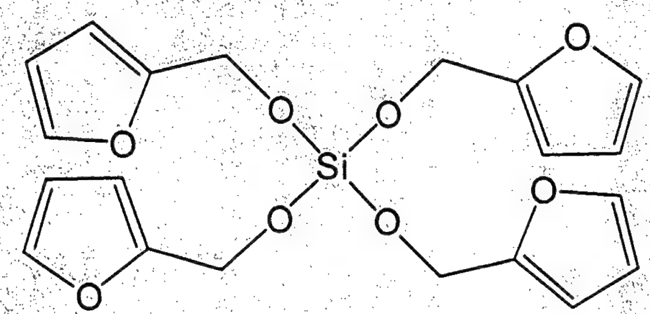
A material formed by re-connectable chemical bonds should be re-mendable.

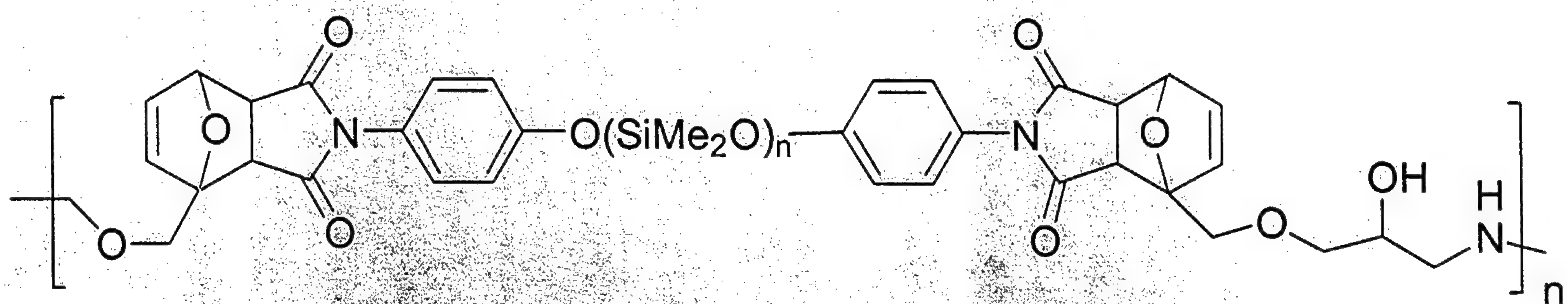



load

Highly cross-linked re-mendable polymeric materials



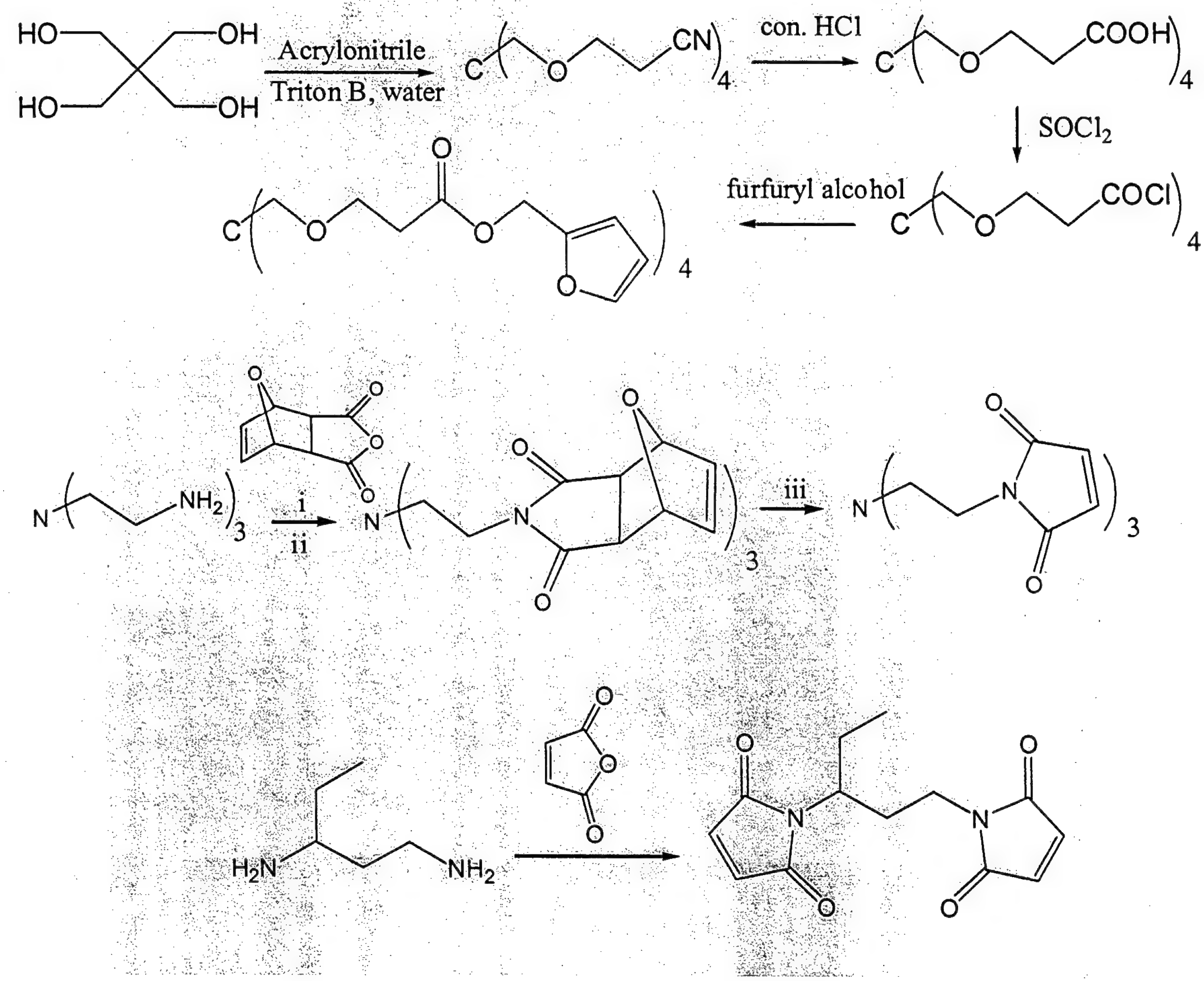




Small, J. H.; Loy, D. A.; Wheeler, D. R. McElhanon, J. R.; Saunders, R. S. *US Patent*, 6,271,335 B1 (**2001**).

Loy, D. A.; Wheeler, D. R.; Russick, E. M.; McElhanon, J. R.; Saunders, R. S. *US Patent*, US 6,337,384 B1 (**2002**).

Synthesis of monomers

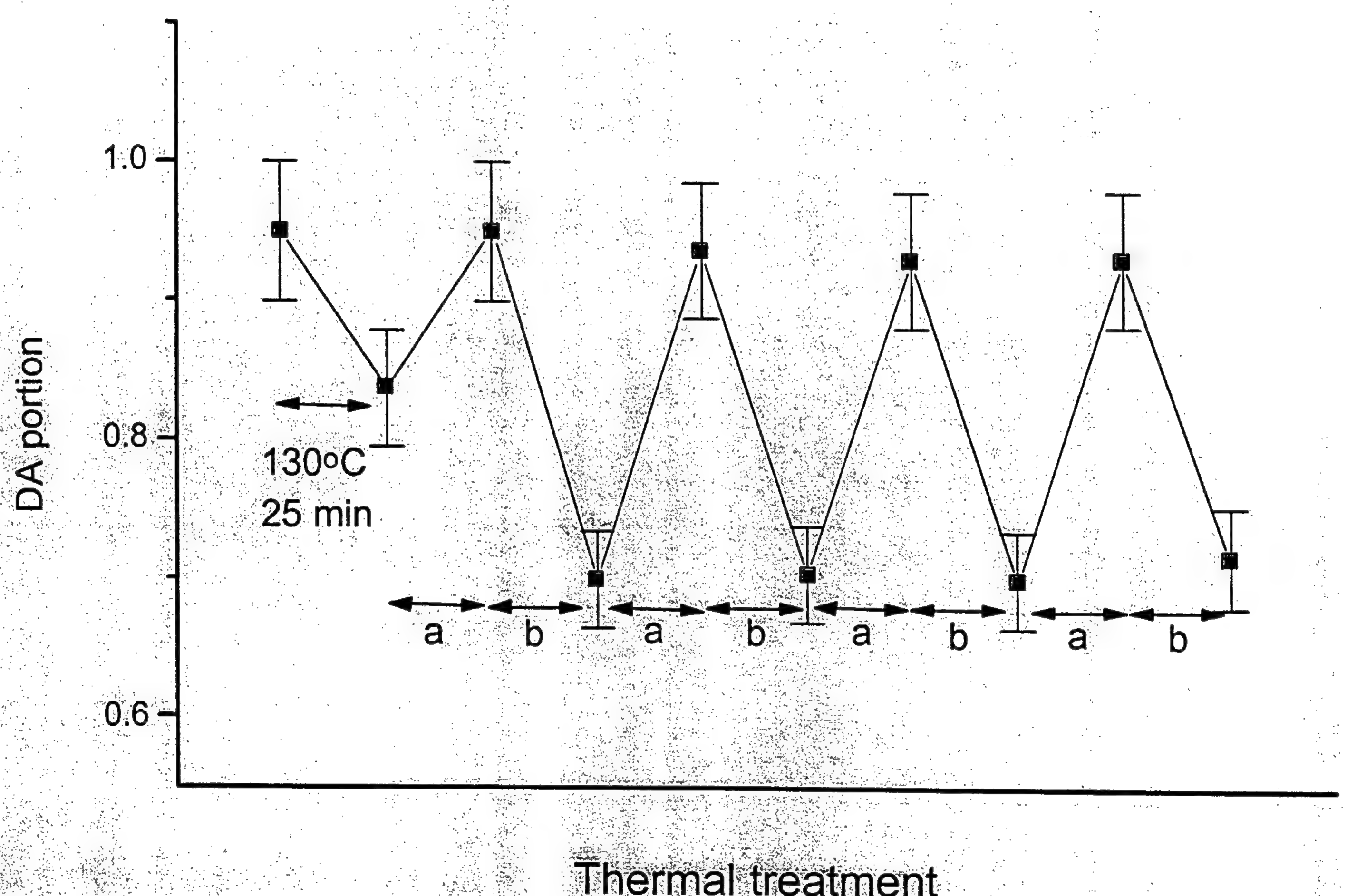


Mechanical properties

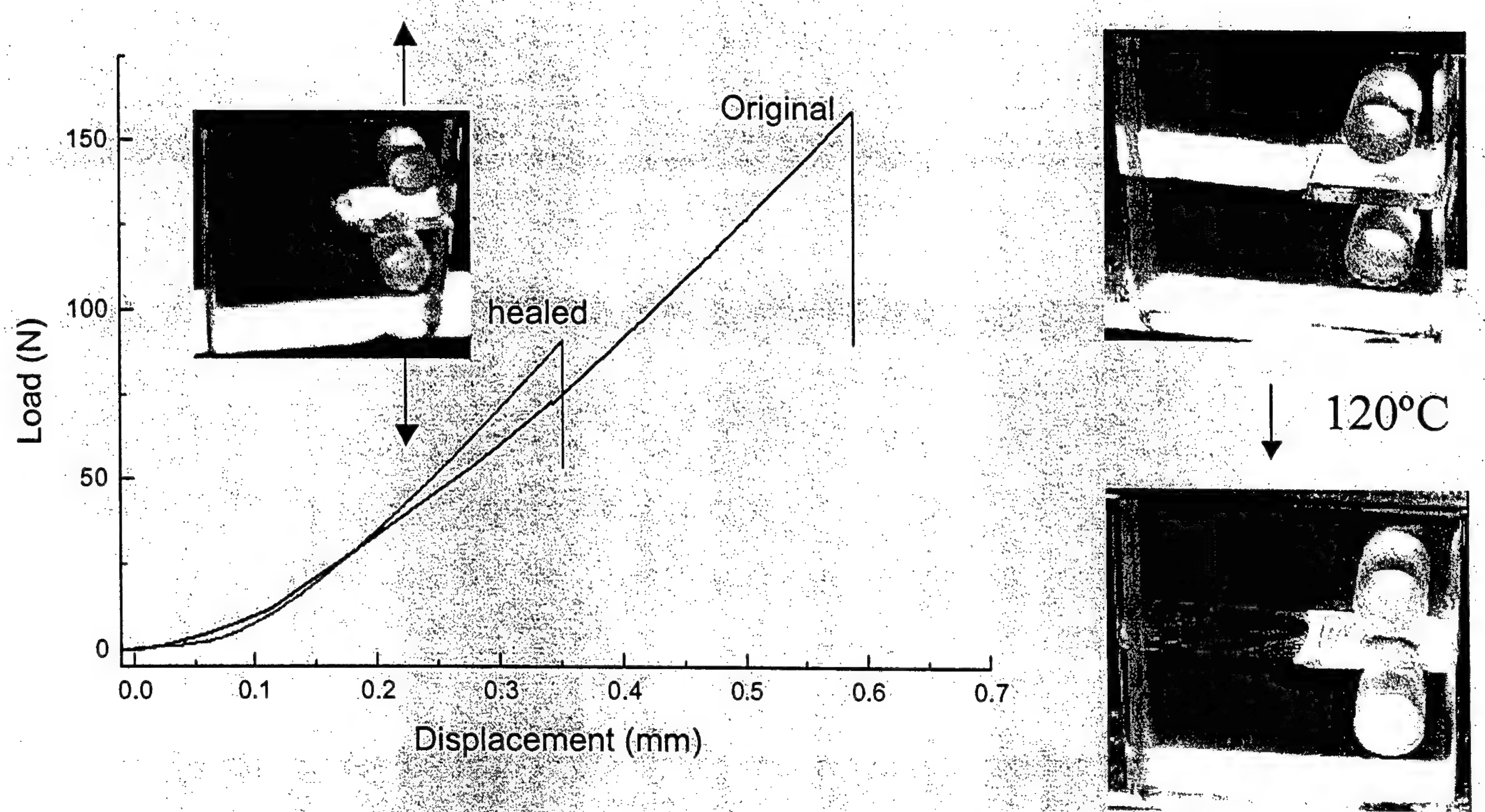
	3M4F	2MEP4F	Epoxy Resins	Unsat Polyesters	ASTM Test methods
Tensile					D638
Strength (MPa)	68		27-88	4-88	
Modulus (GPa)	--		2.4	2-4.4	
Elongation (%)	1.6-4.7		3-6	<2.6	
Ultimate Tensile (MPa)	241	234			
Compression					D695
Strength (MPa)	121		102-170	88-204	
Modulus (GPa)	3.6	3.7	3.4		
Strain to Failure (%)	25	24			
Flexural					D790
Strength (MPa)	143		88-143	58-156	
Modulus (GPa)	3.5			3.4-4.2	
Young's Modulus (GPa)	4.72	4.41			
Poisson Ratio	0.32	0.36			
Density	1.37	1.31			

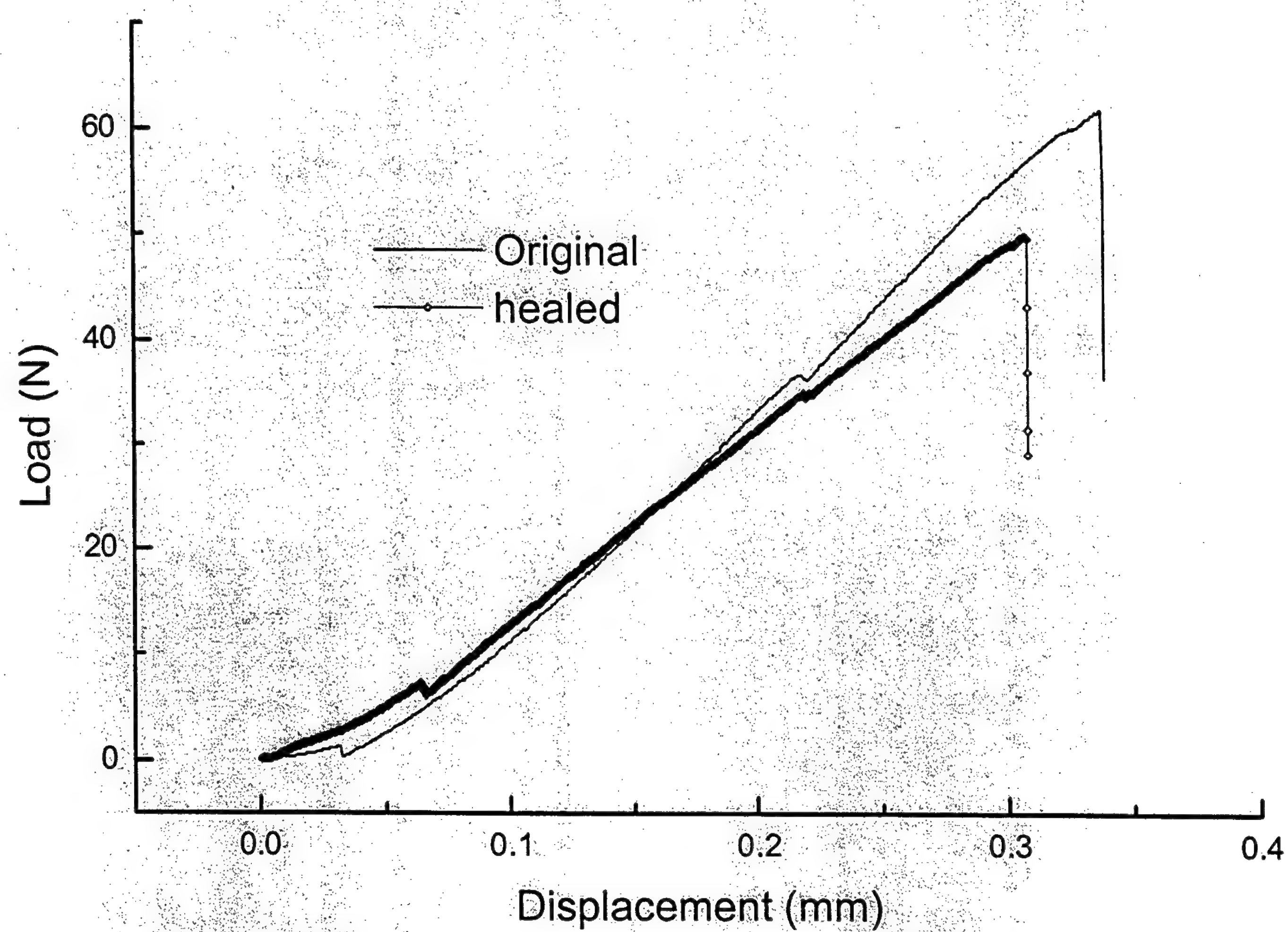
Thermal reversibility of polymer 3M4F

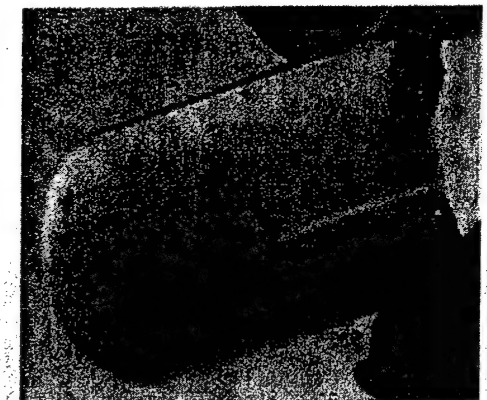
(a)80?C, 1 h; (b)150?C, 15 min and then quenched in 77K



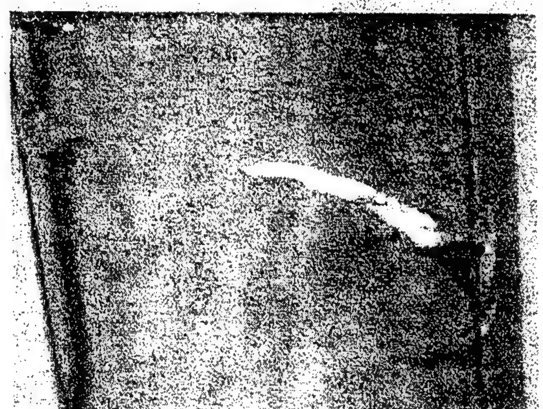
Healing (mending) efficiency of polymer 3M4F




Original
healed
Load (N)
60
40
20
0
0.0
0.1
0.2
0.3
0.4
Displacement (mm)



Healing effect



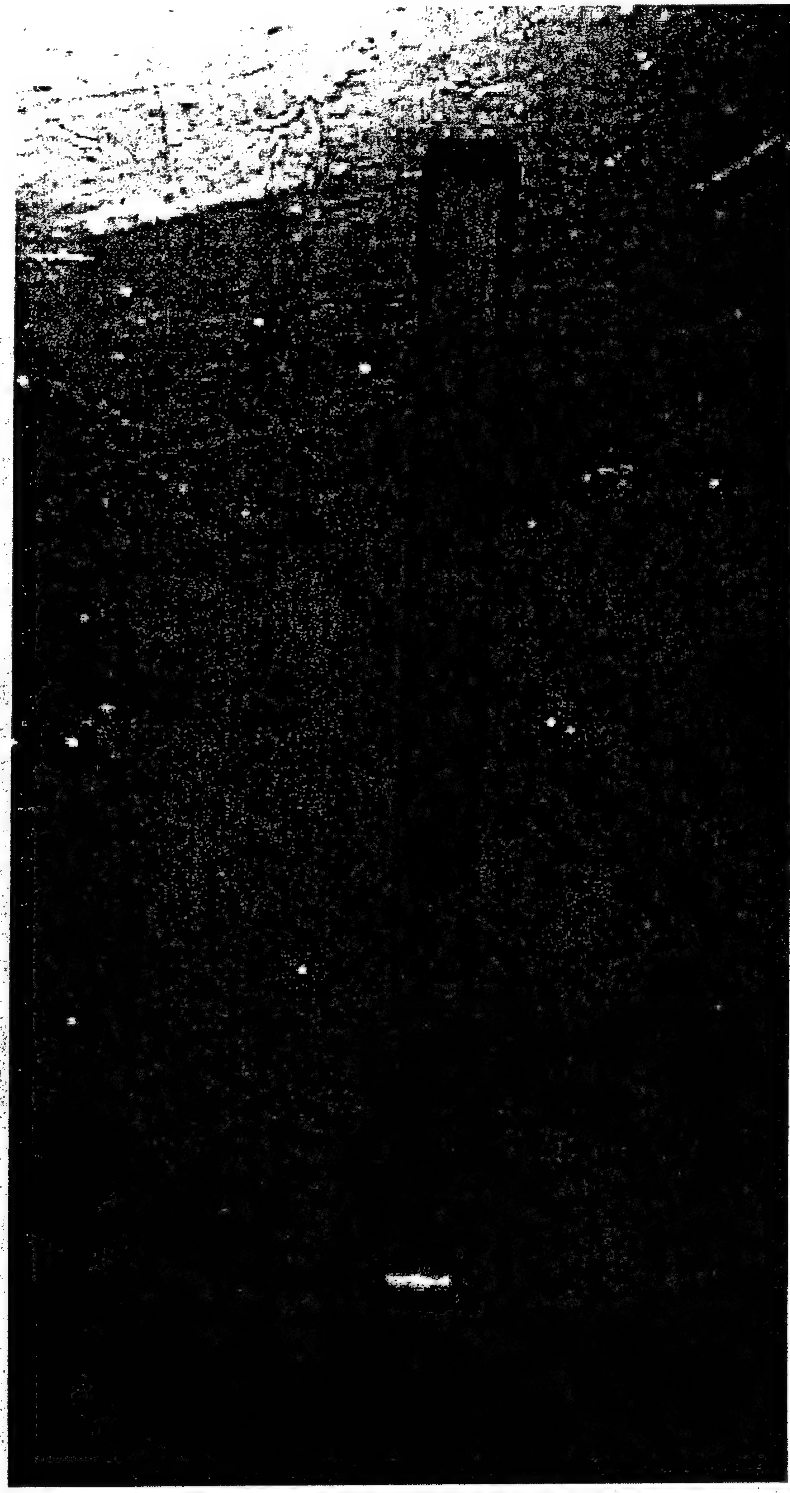
heat →

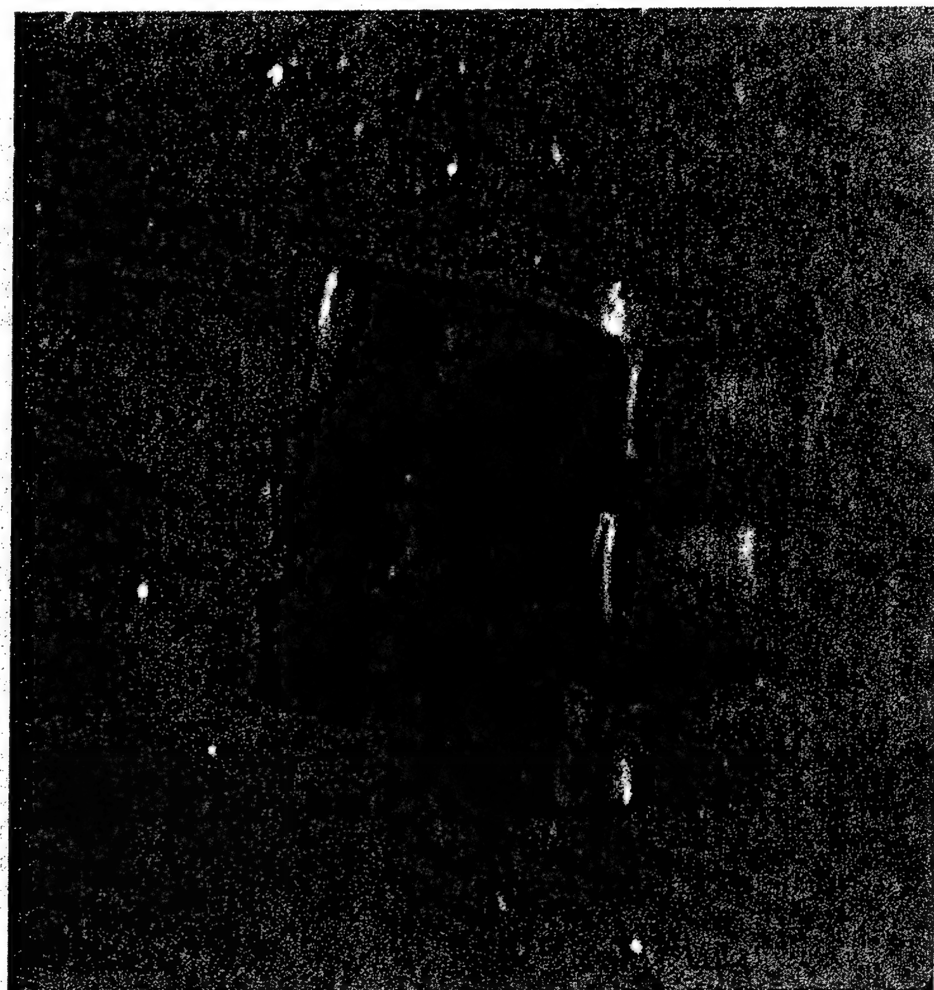
Summary

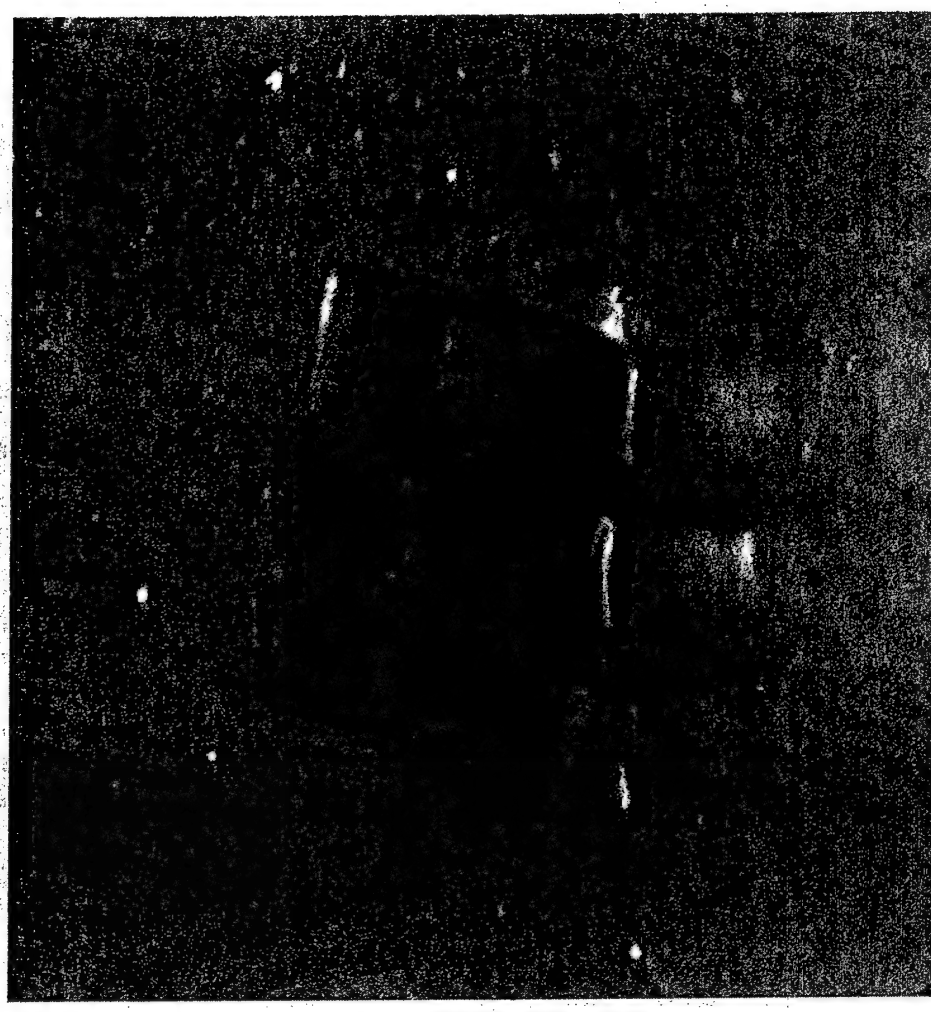
Thermally re-mendable polymers have been developed, which can be healed multiple times. The healing process does not require additional ingredients.

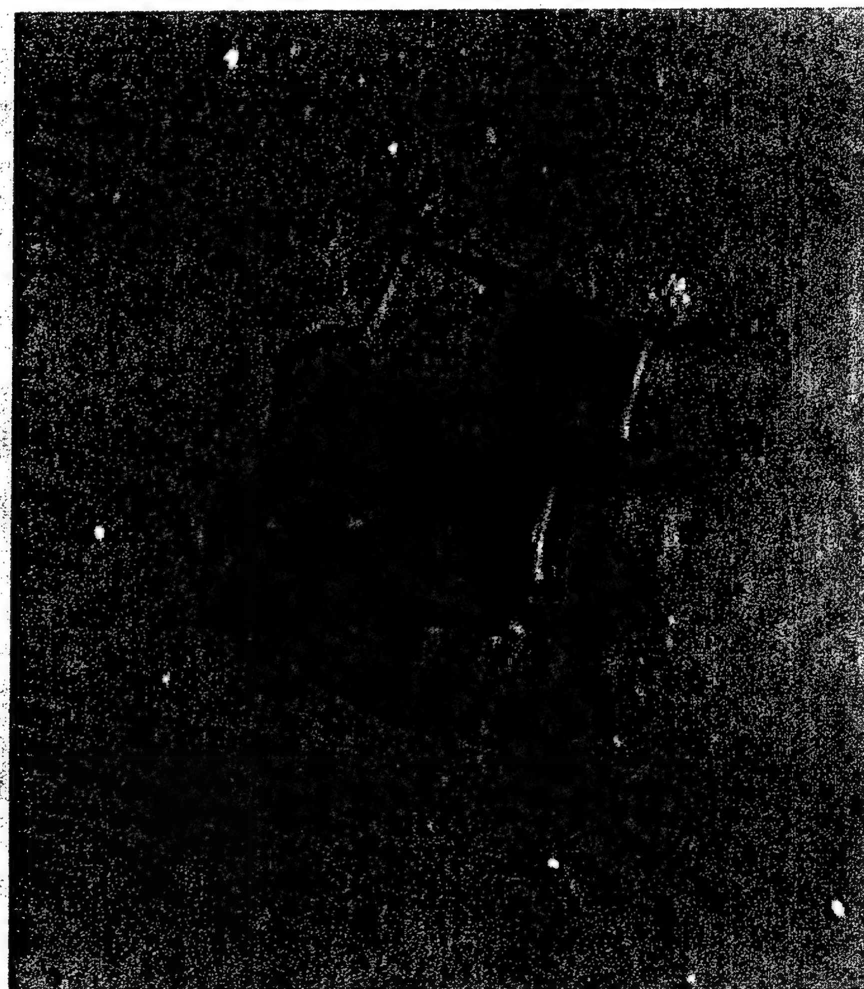
Future designs of re-mendable polymeric materials

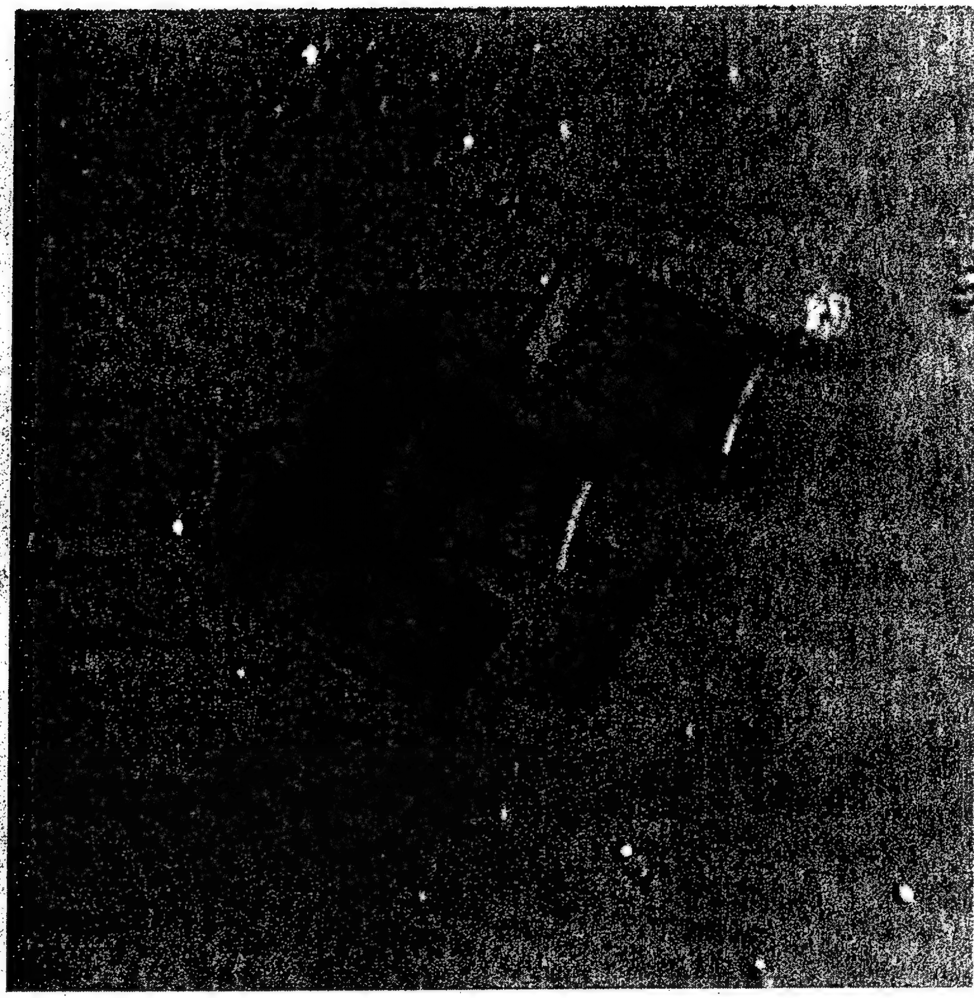
- Better mechanical properties
- Higher glass transition temperature
- Smart structures with self-response ability (shape memory)

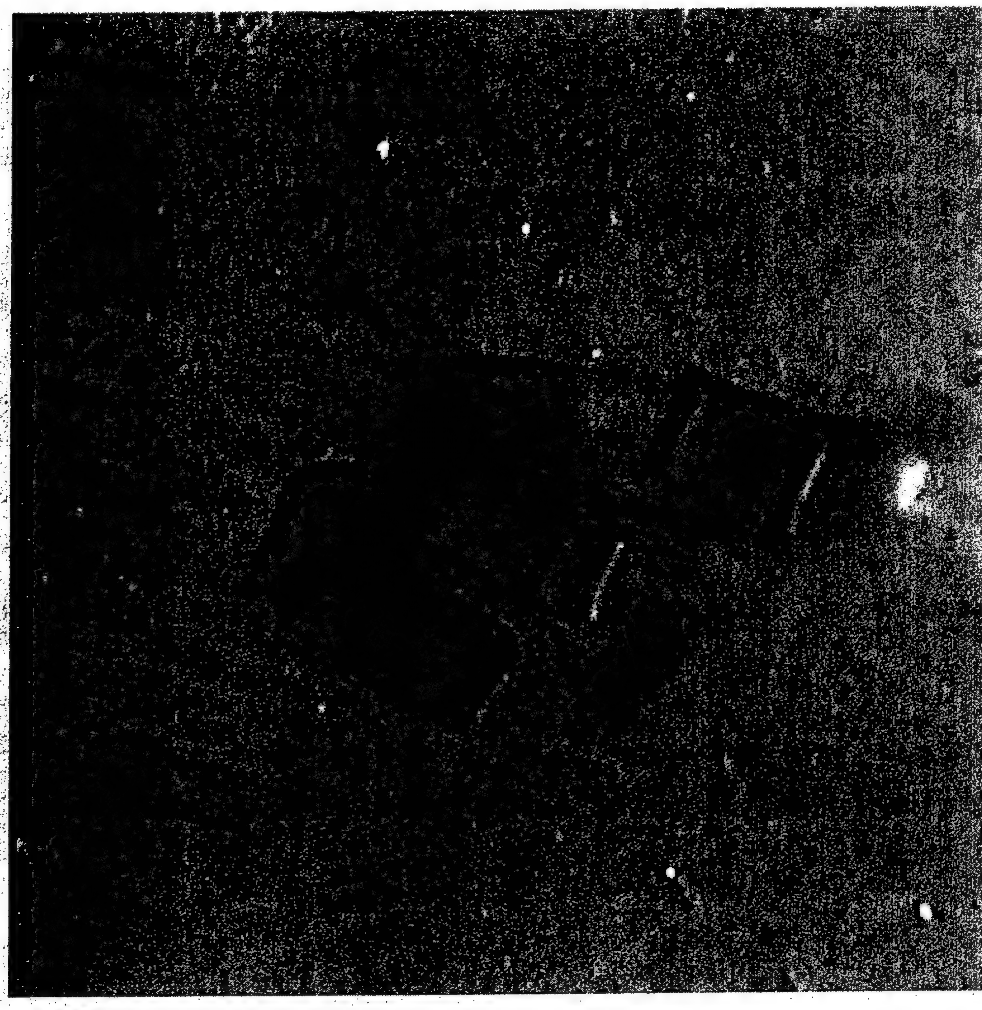


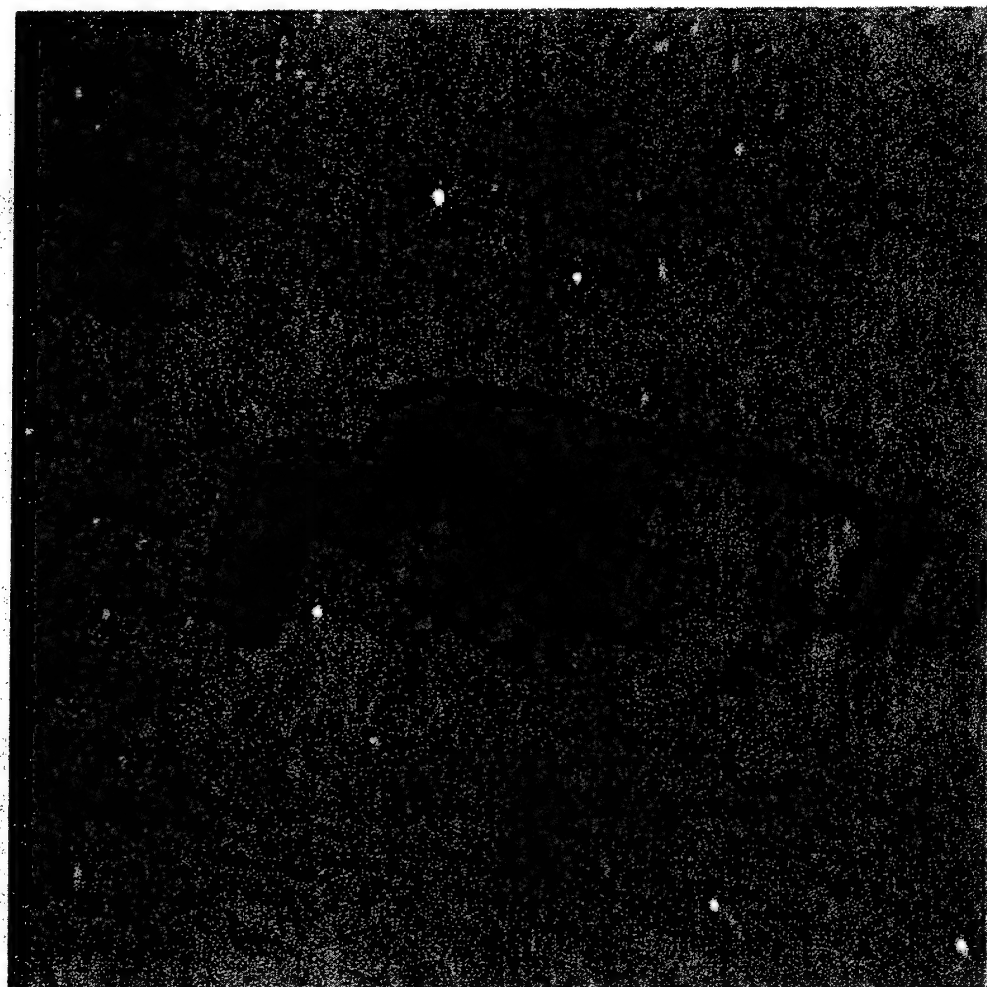


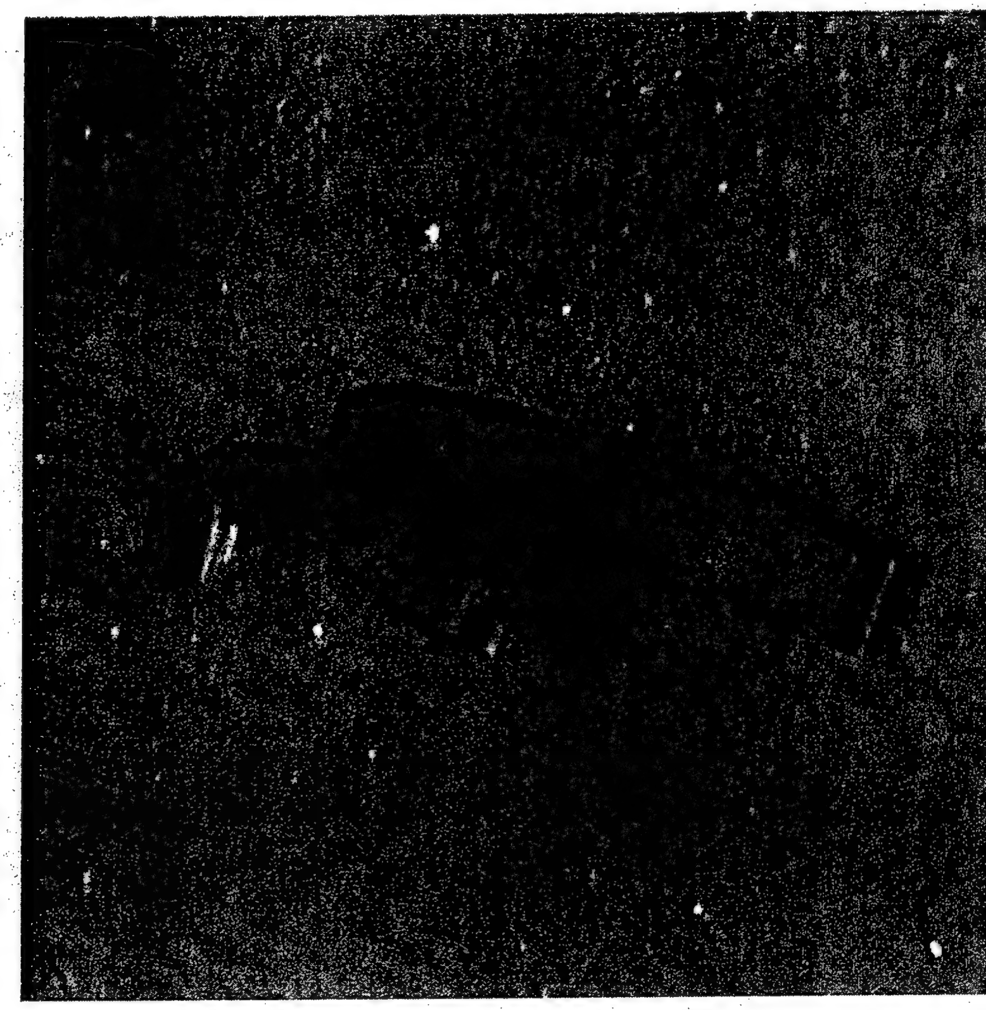


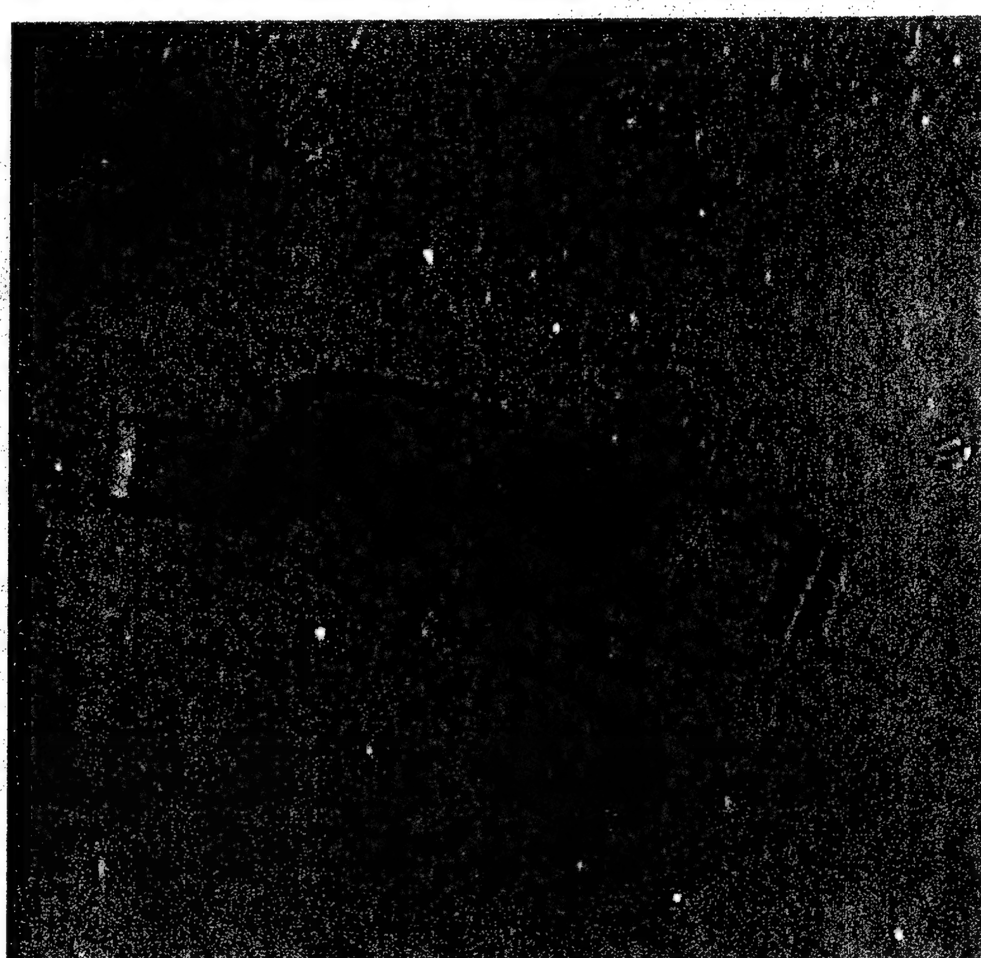


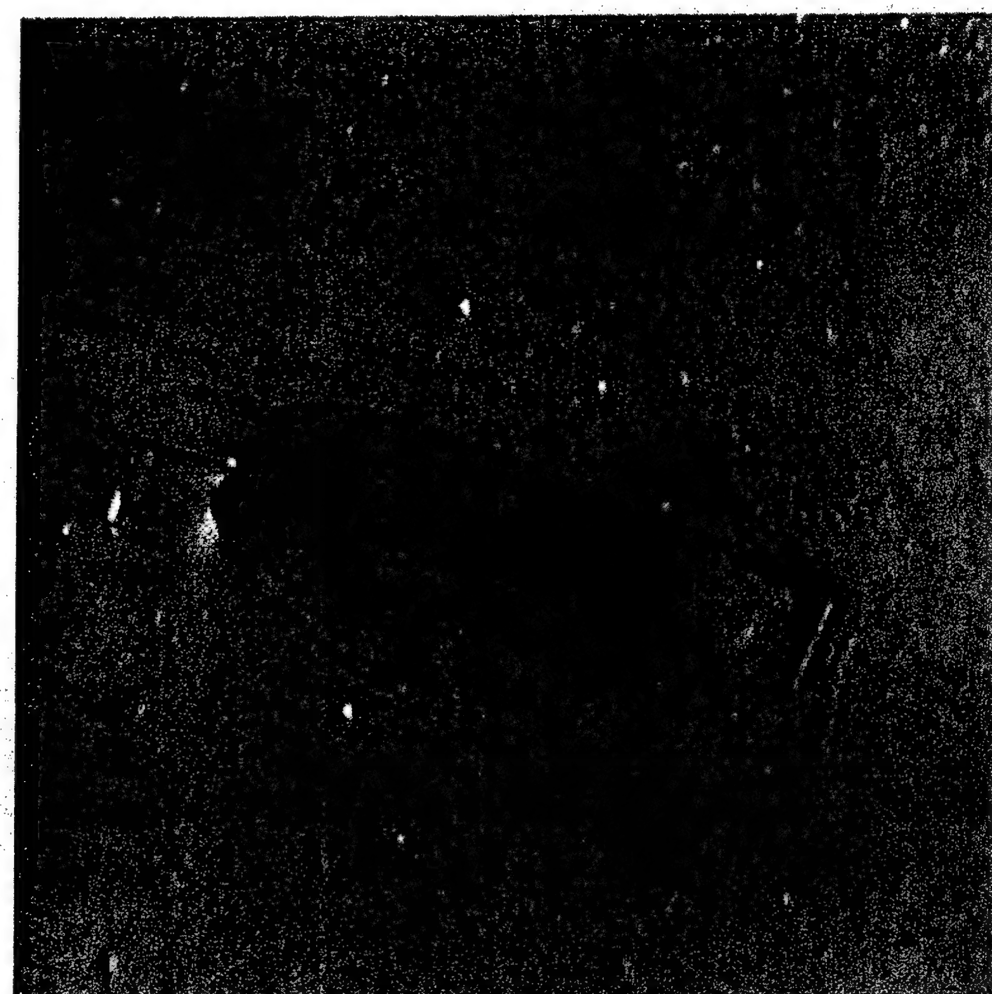


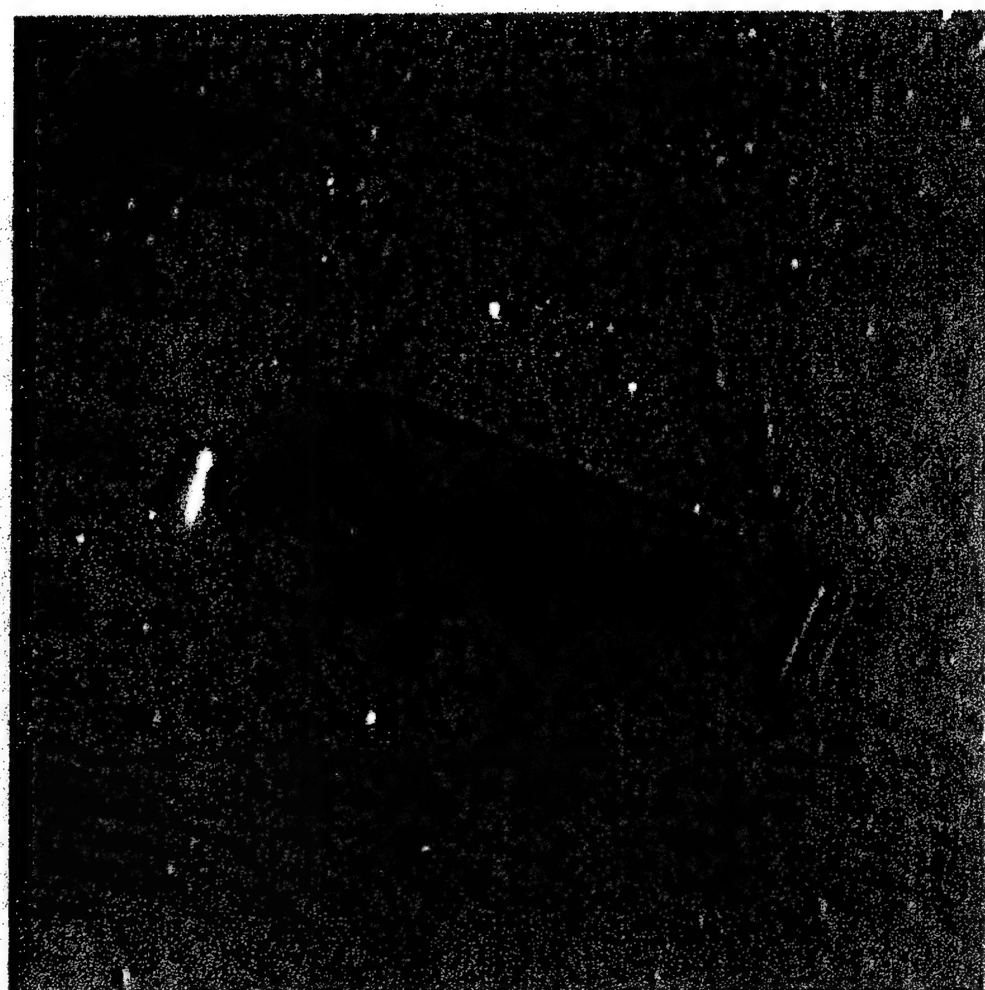


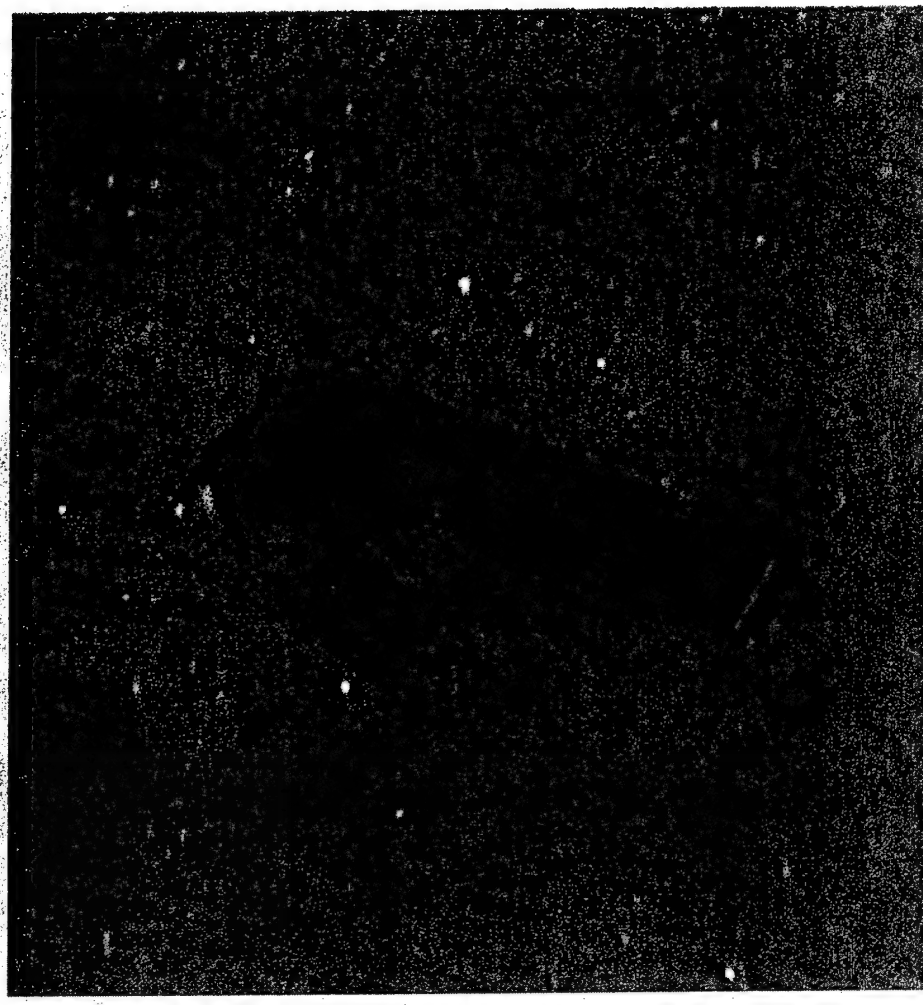


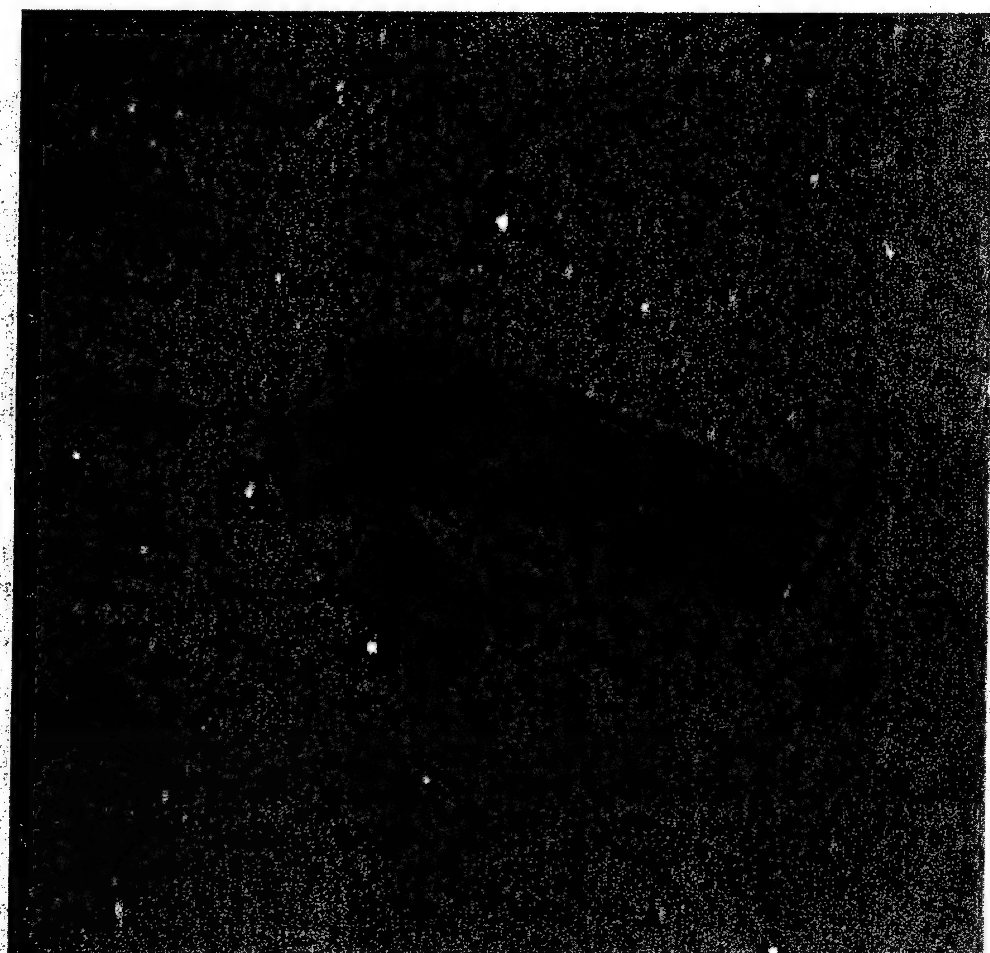


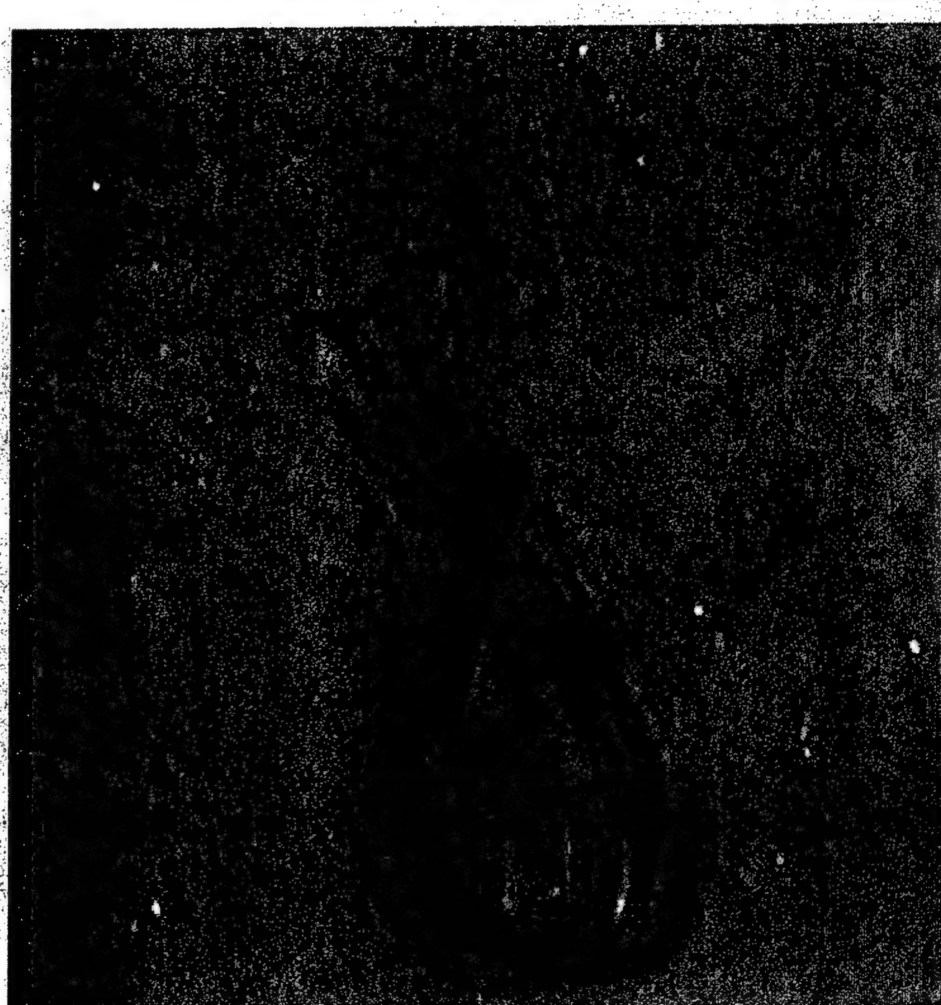


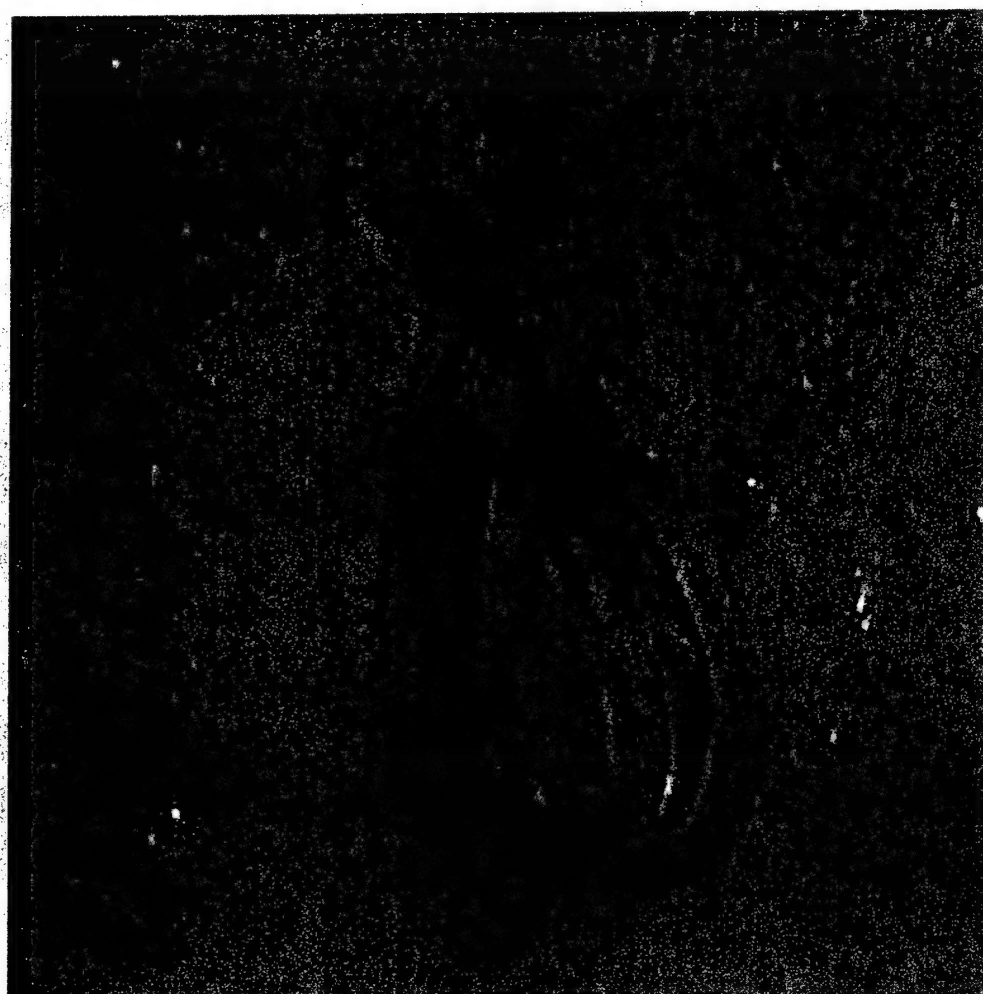


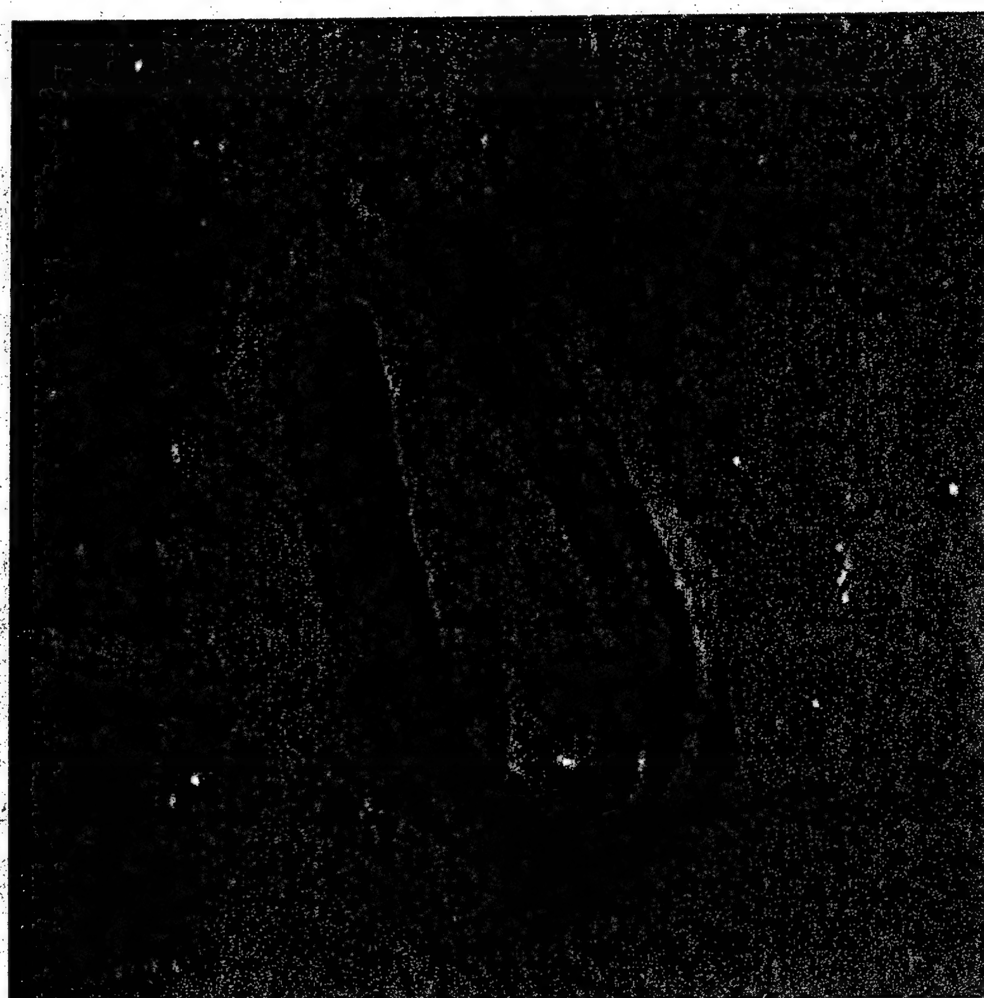


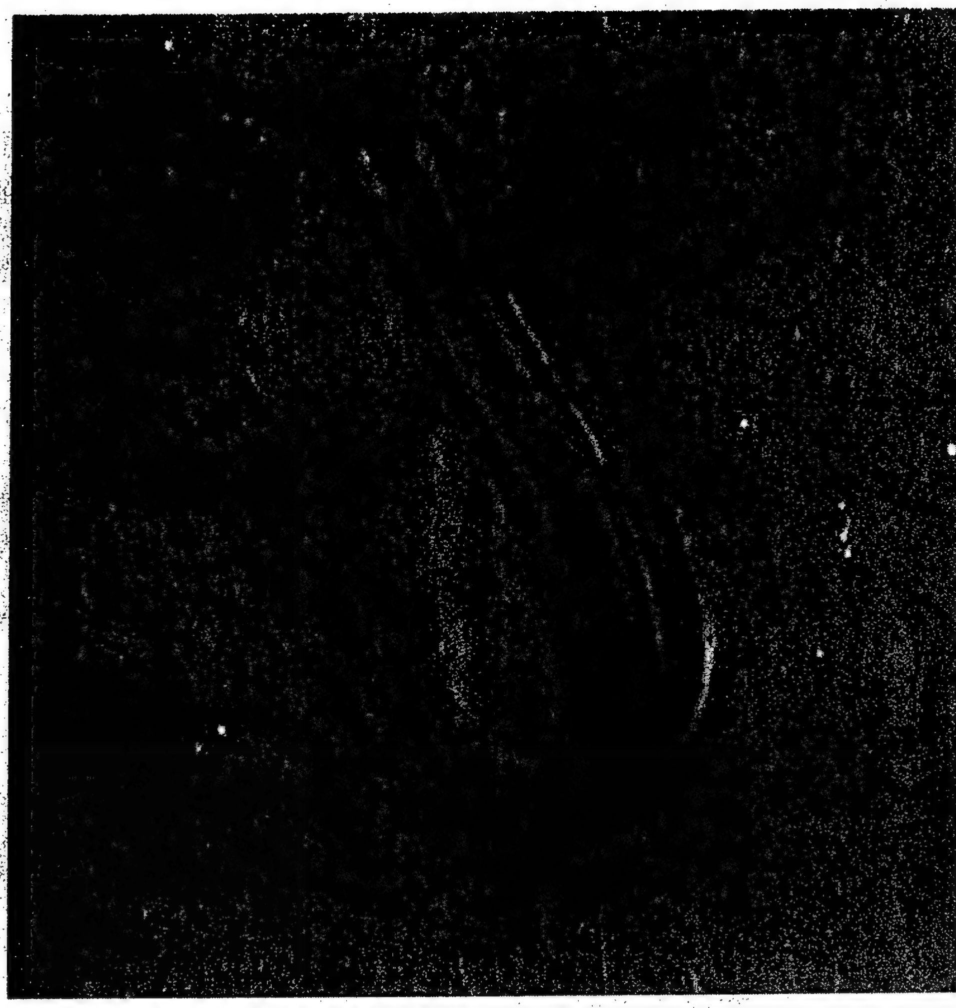


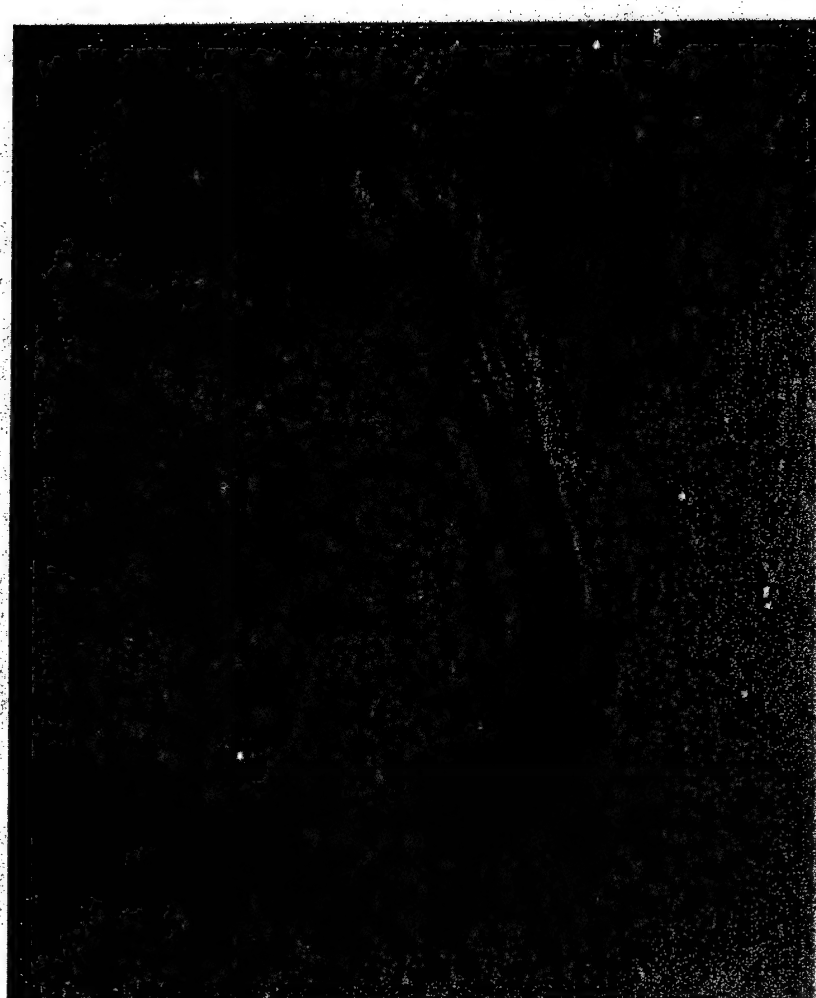


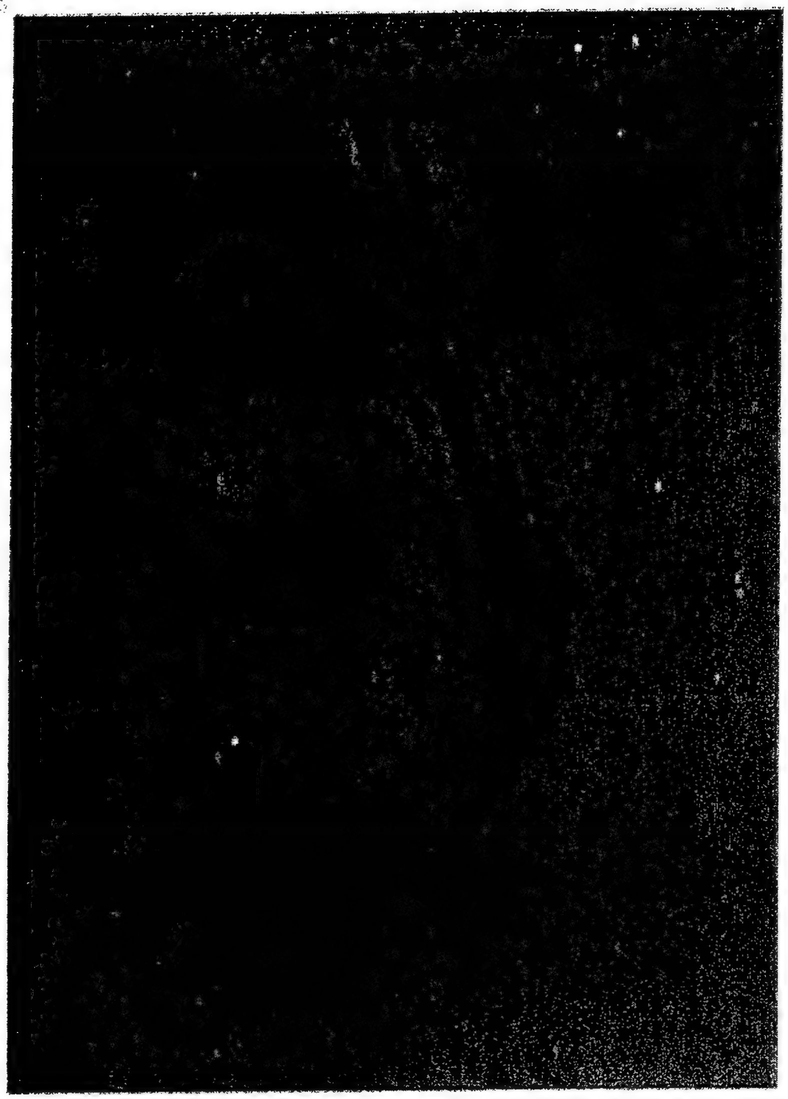


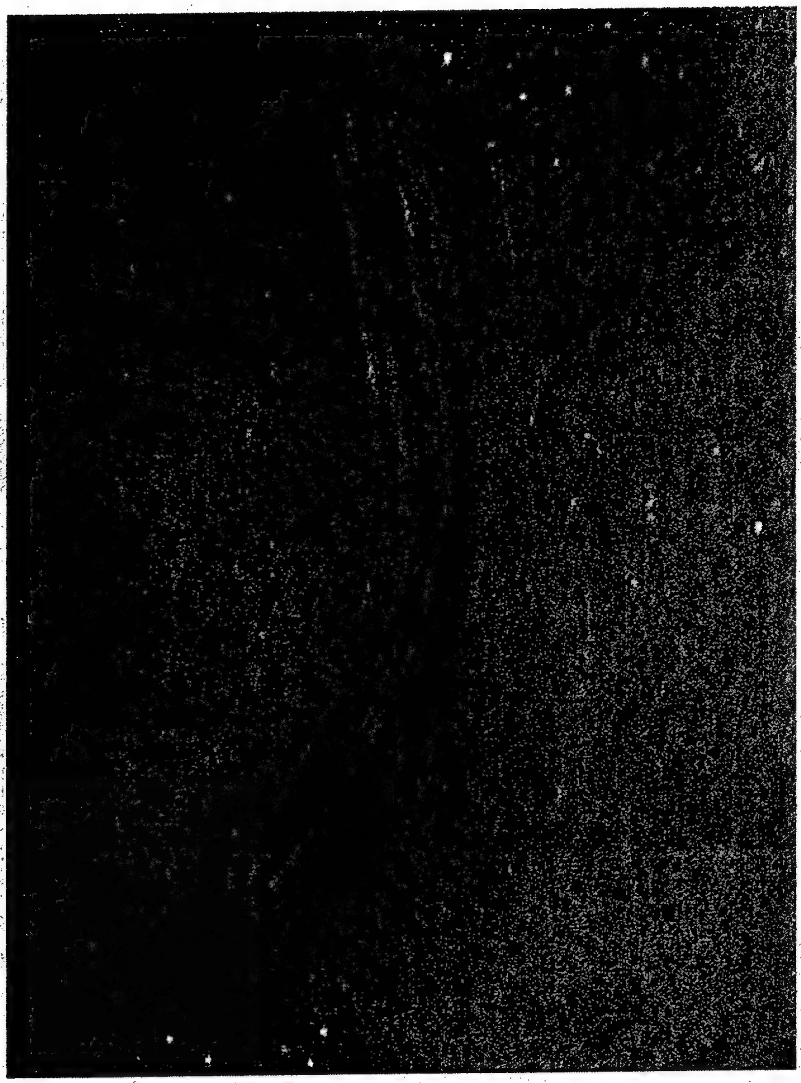


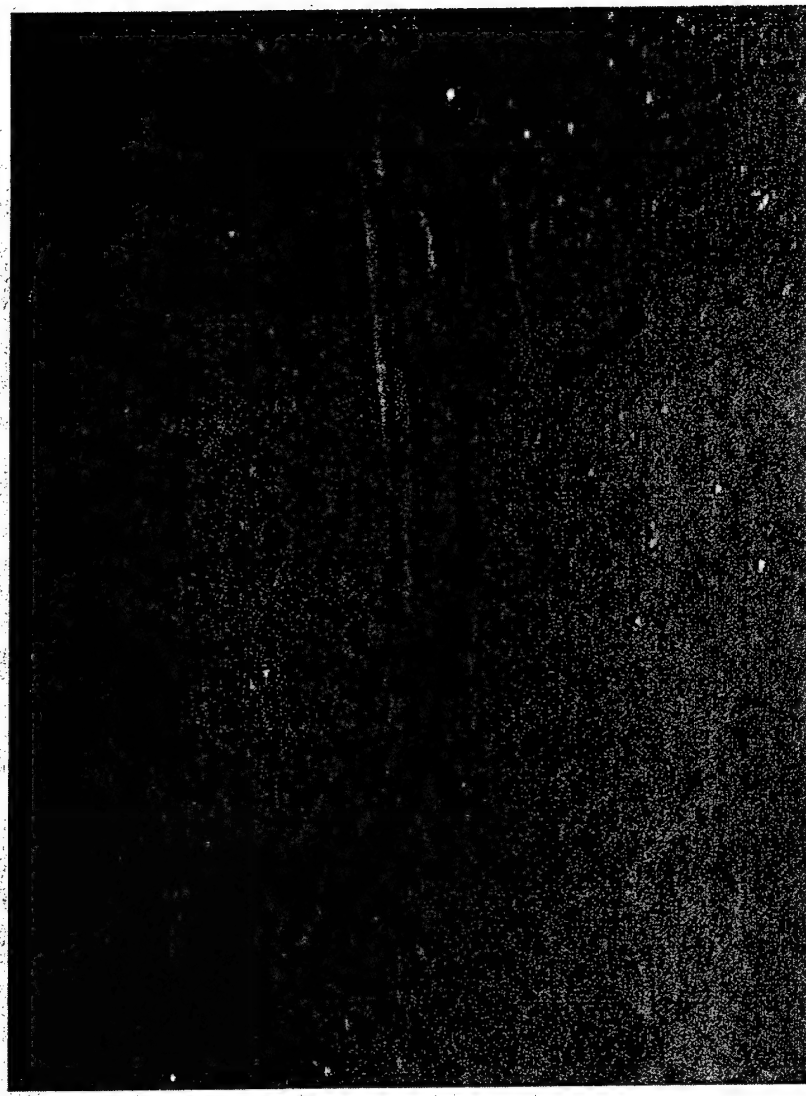


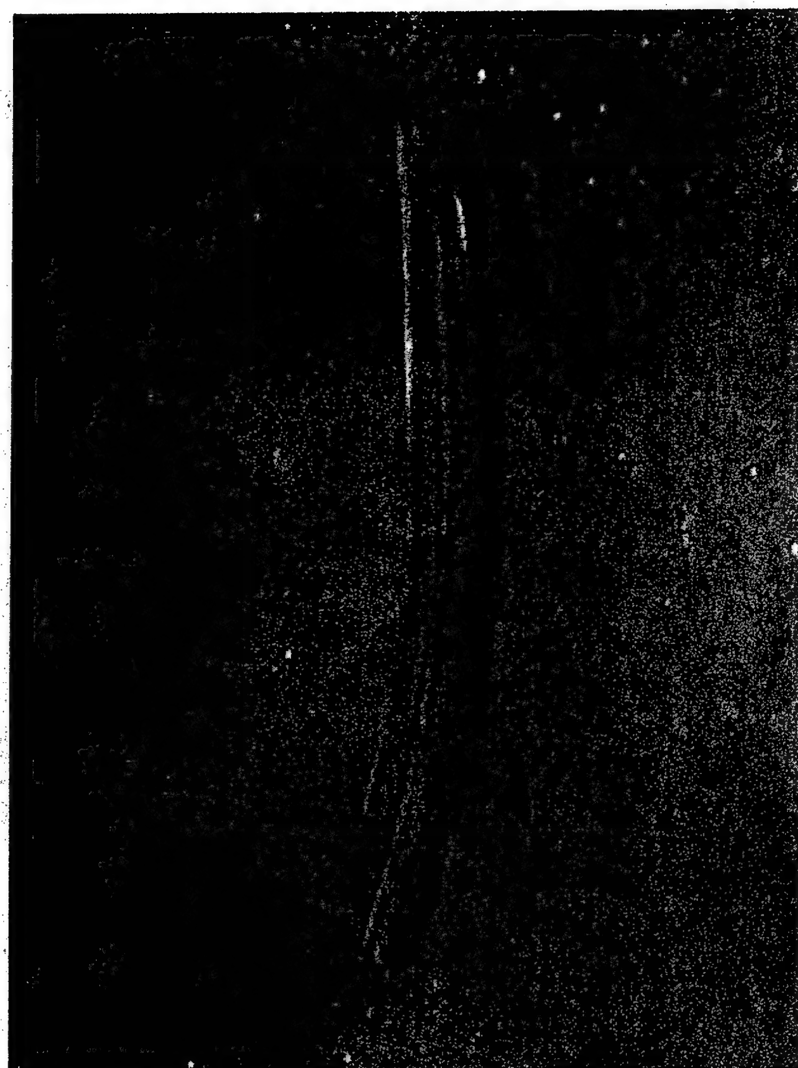


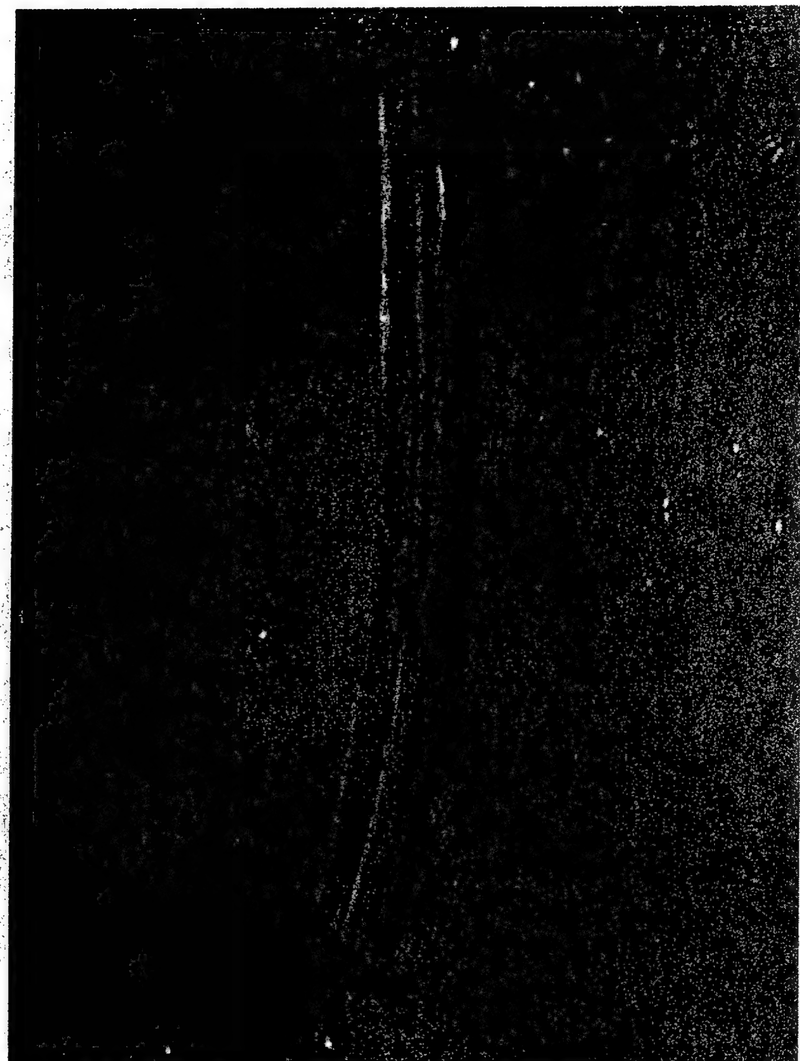


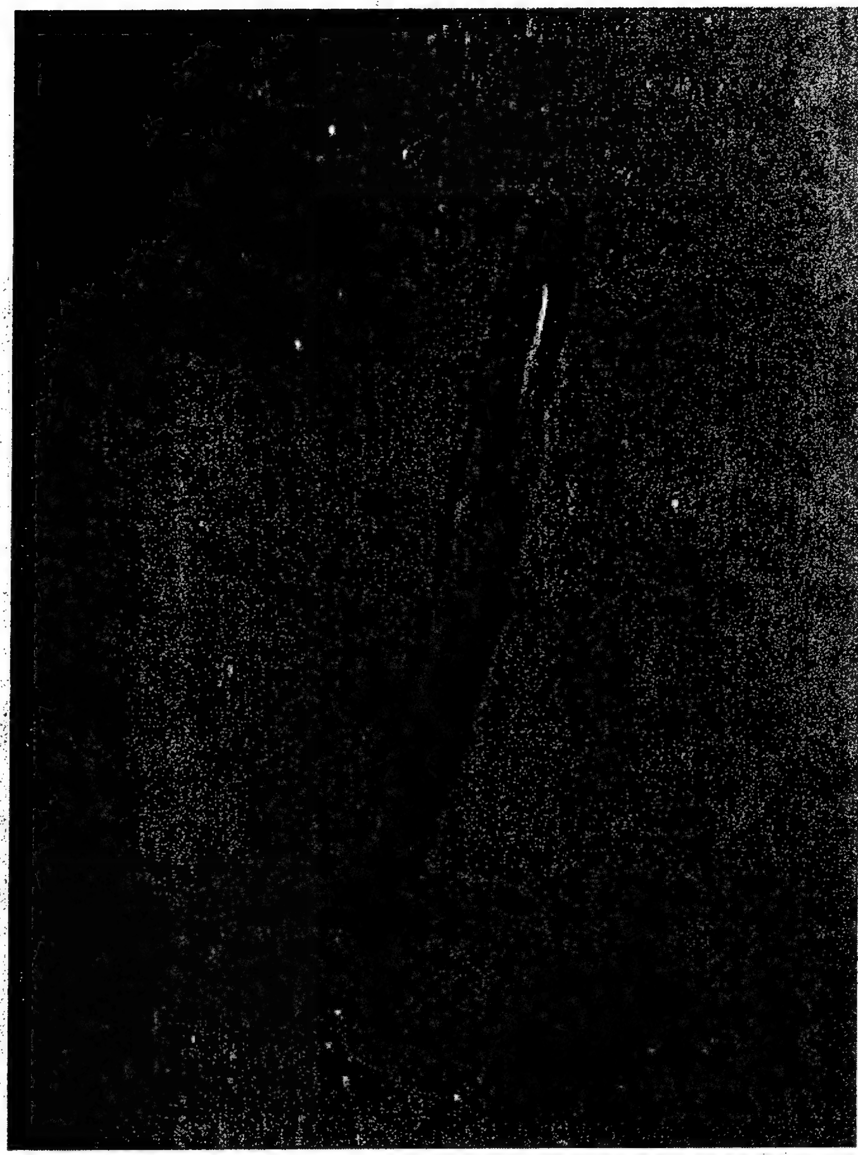


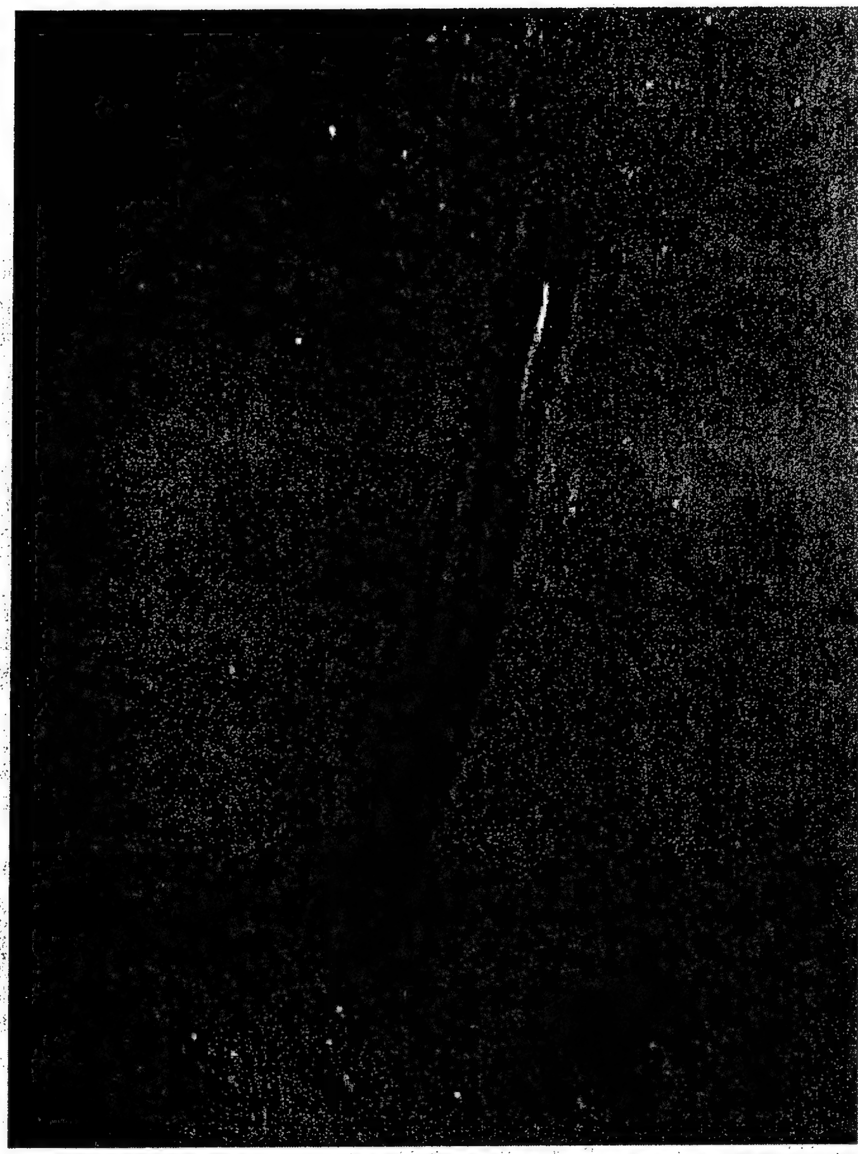












Acknowledgments

UCLA

Professor Fred Wudl

Prof. Ajit Mal

Prof. Kanji Ono

USC

Prof. Steven R. Nutt

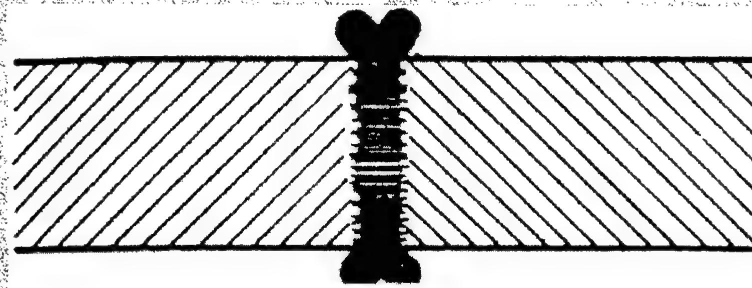
$$$ NSF $$$

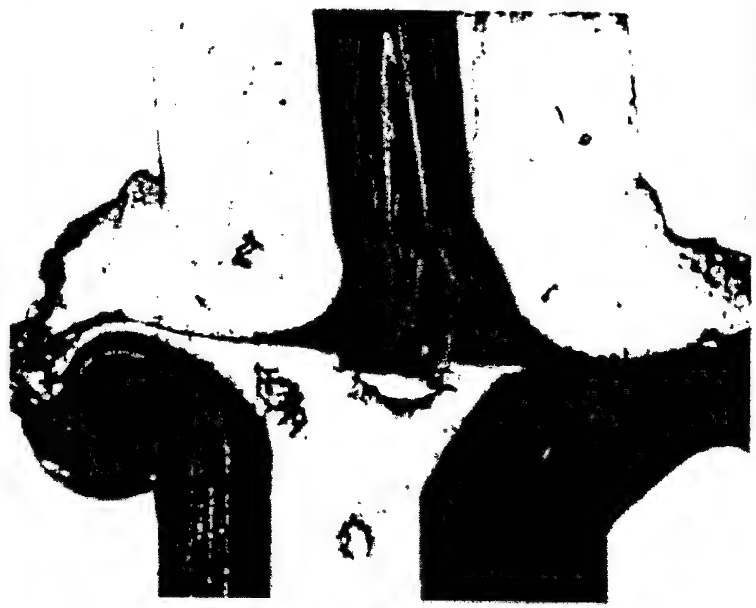
Differences of healing process between our re-mendable polymers and linear polymers

Regeneration of chain entanglement is necessary for linear polymers

Much higher operating temperatures (PP: 250 -300°C)

Manual pressure





Bucknall, C. B.; Drinkwater, I. C.; Smith G. R. *Polym. Eng. Sci.* 20, **1980**, 432.

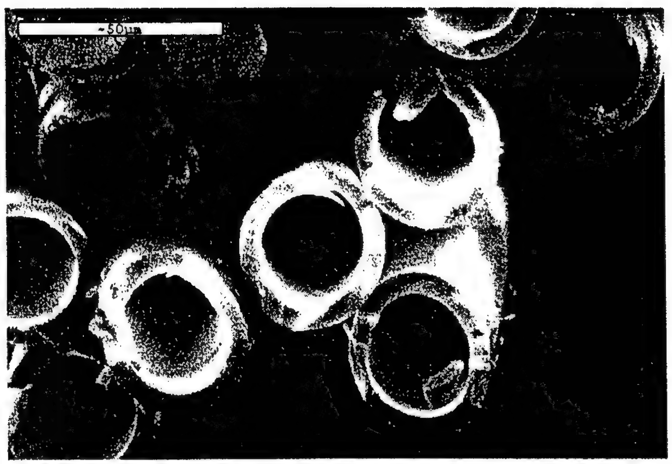
Novel and Multi-Functional Composites

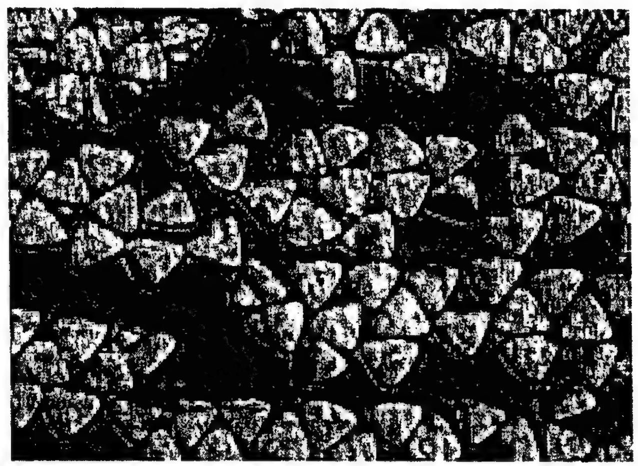
Michael Wisnom

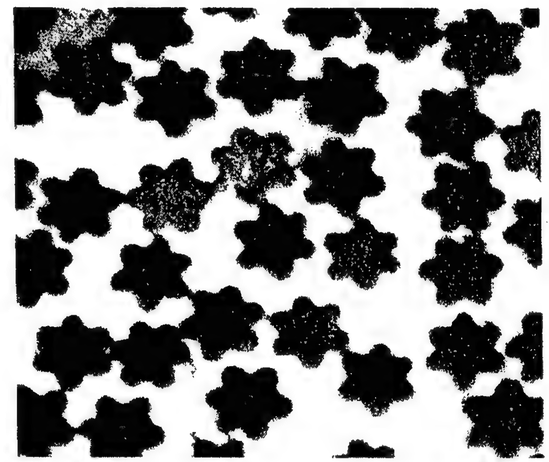
and

Ian Bond

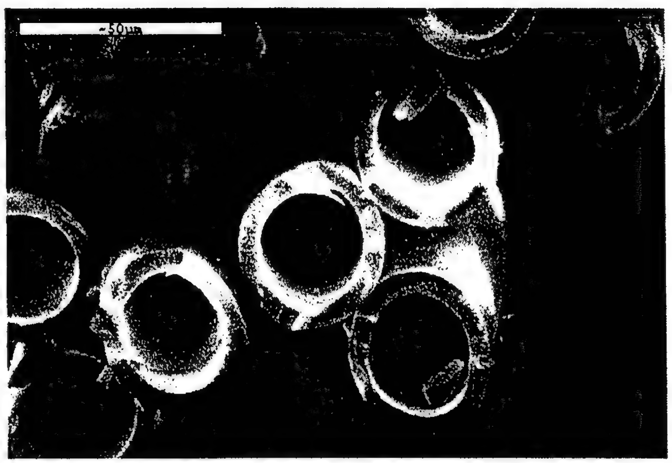
Shaped fibres made at Bristol





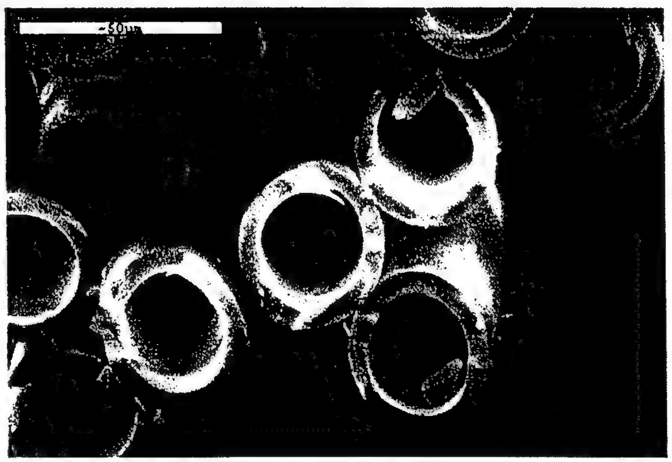


Impact detection with hollow fibre composites



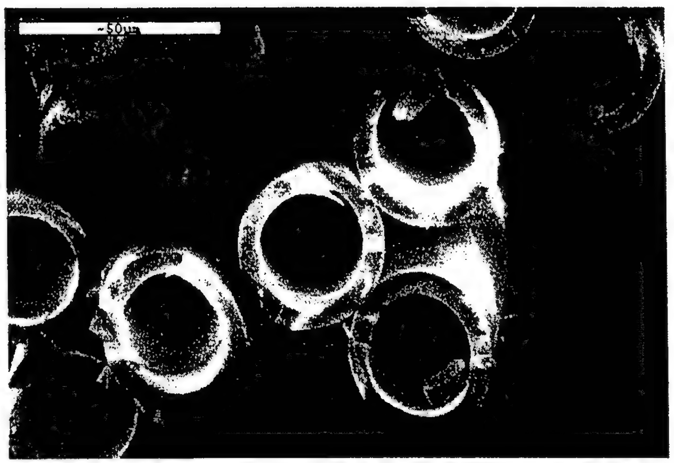
- Hollow fibre layer on surface of structure
- Fibre crushing absorbs impact energy
- Leaves visible dent
- Layer can be tuned to impact severity

Active fibres



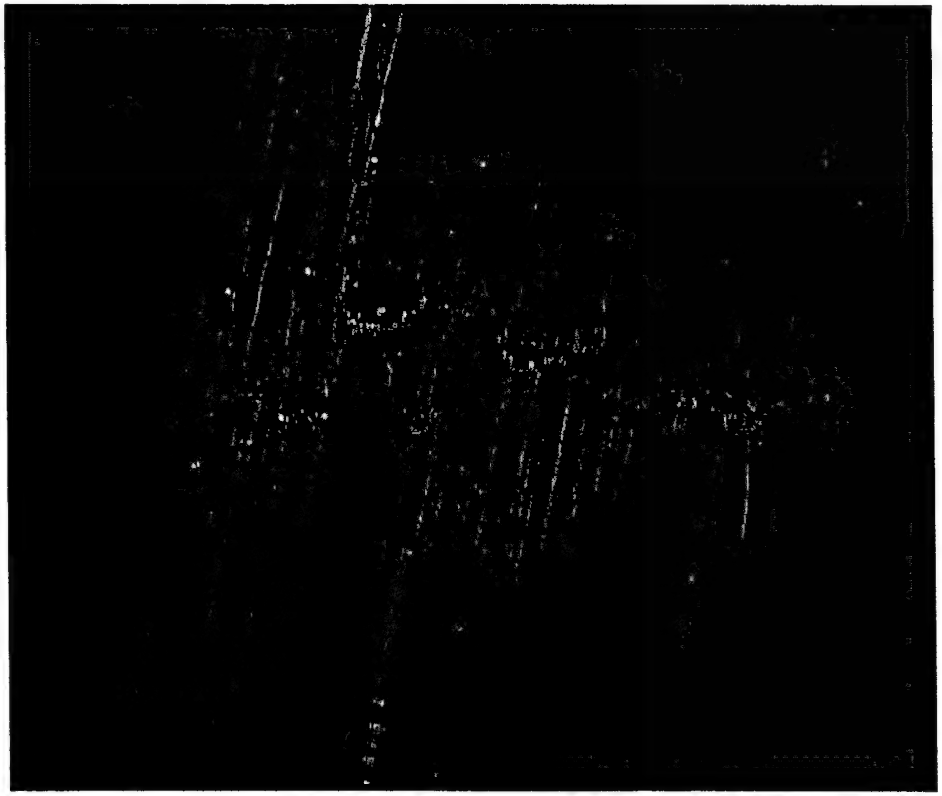
- Fibres can be filled with active component to create multi-functional composites
  - Magnetic material for electric generation
  - Stealth

Bleeding composites



- Fibres can be filled with dye that bleeds out and allows damage to be detected
- Uncured resin in fibres can act as healing agent

Bleeding composites



- Fluorescent dye mixed with uncured resin
- Impact damage clearly visible under UV light

Self-healing and Electronic Assemblies

Andrew Skipor
Distinguished Member of the Technical Staff

Mechanical Sciences Group
Motorola Advanced Technology Center
Schaumburg, IL
847-576-0754

1st AIR FORCE WORKSHOP ON
"MULTIFUNCTIONAL AEROSPACE MATERIALS"
October 23-24, 2002, Purdue University,
W. Lafayette, IN

MOTOROLA LABS

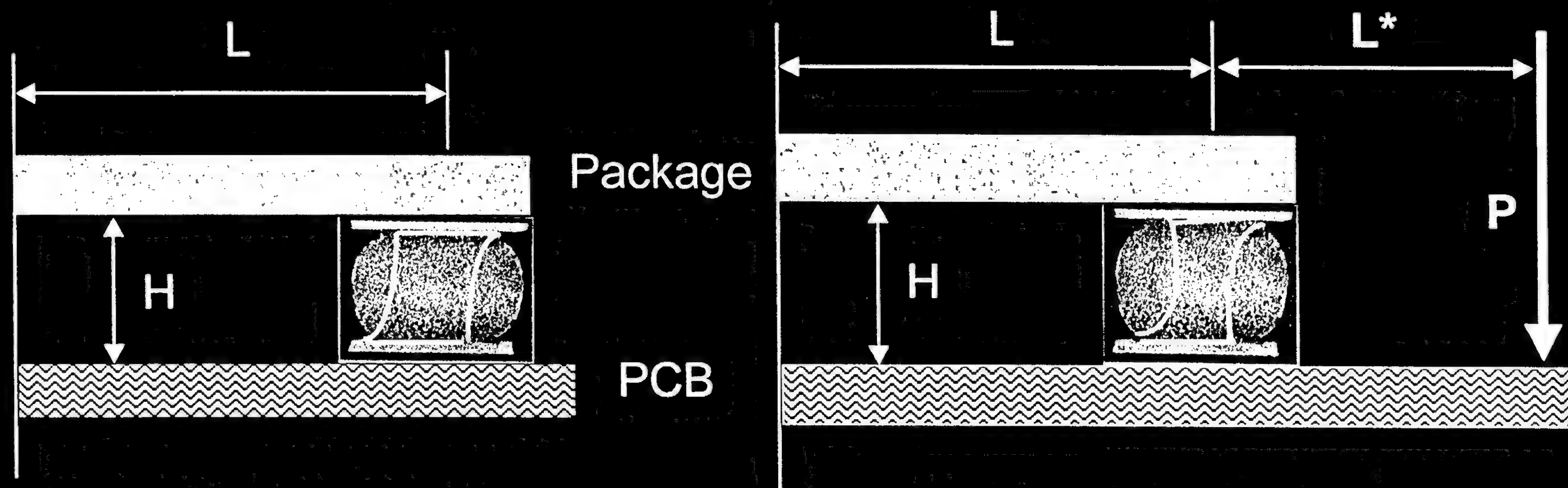
intelligence everywhere™

Self-Heal Materials:

Imagine a future when our products get damaged, they heal themselves.

Interconnect Stress: Background

Bending Fatigue vs. Thermal Fatigue



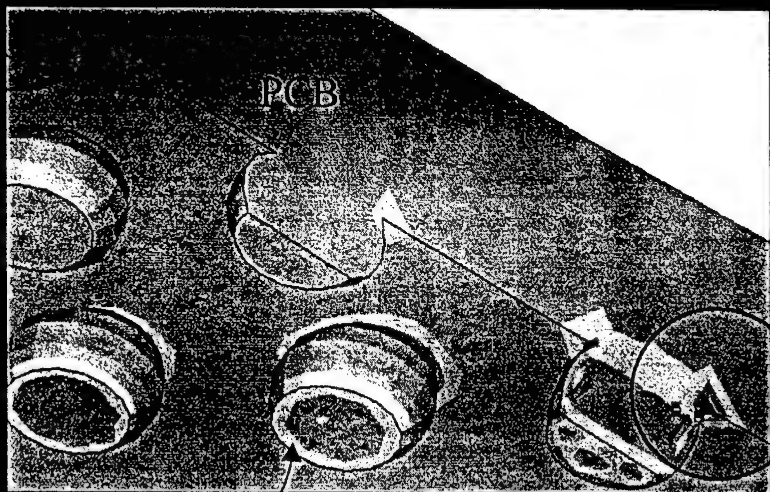
Solder strain drivers:
~ $(\alpha 1-\alpha 2)$, ΔT

Thermal Fatigue Reliability

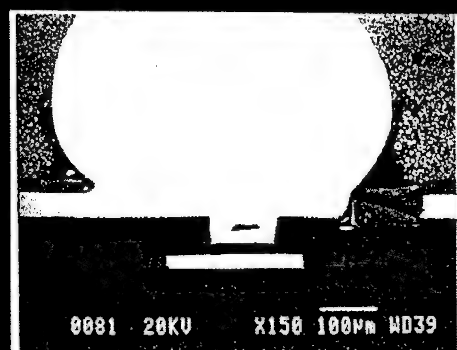
Solder strain drivers:
~ ΔP (load or deflection), L^*

Bending Fatigue Reliability

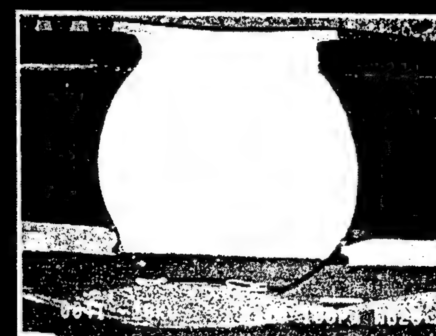
Examples of interconnect resin fracture



Mechanical bend fatigue.



Drop impact, high rate flexure.



"Squeeze" test.

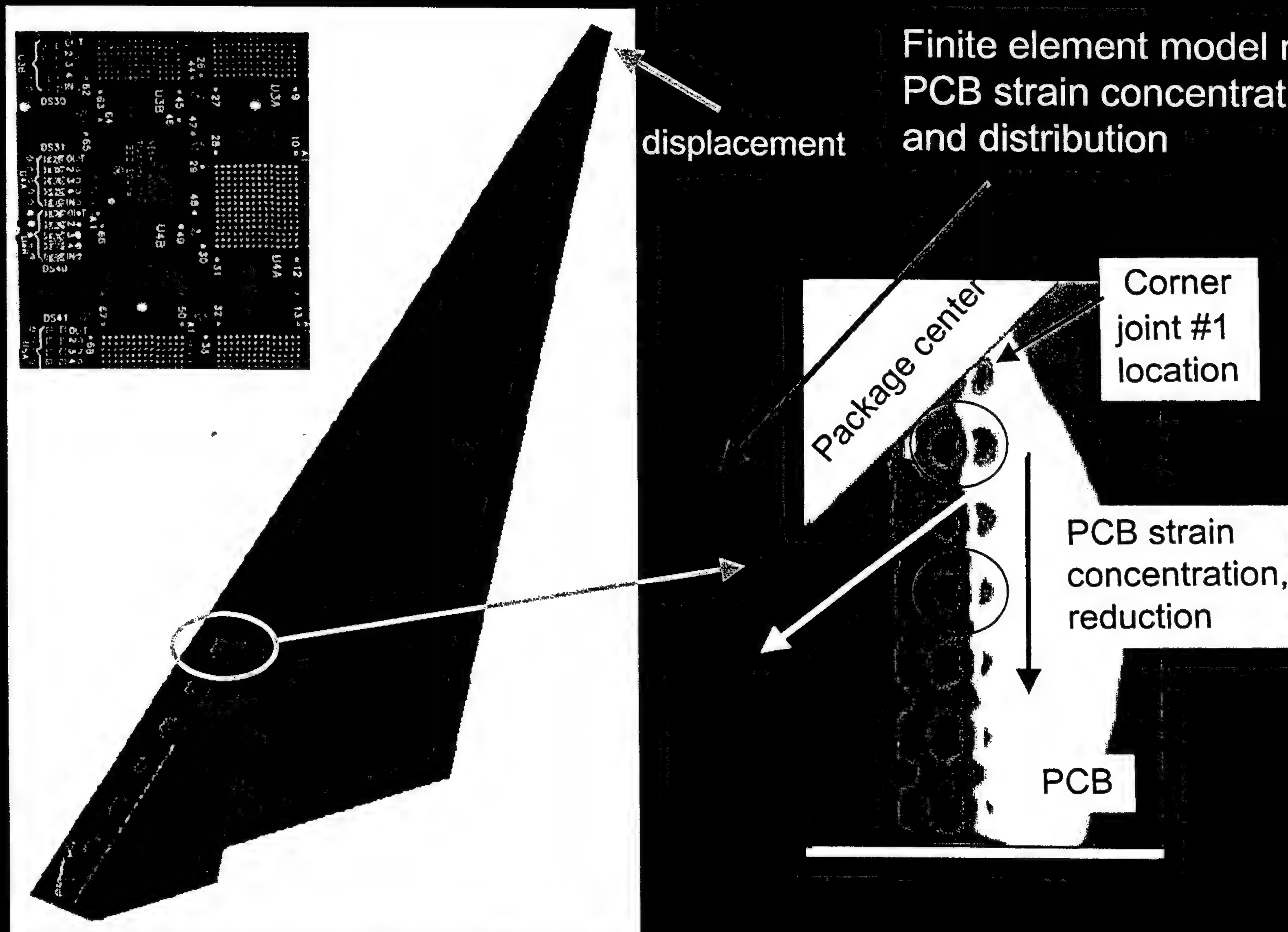
Electronic Package

PCB

MOTOROLA LABS

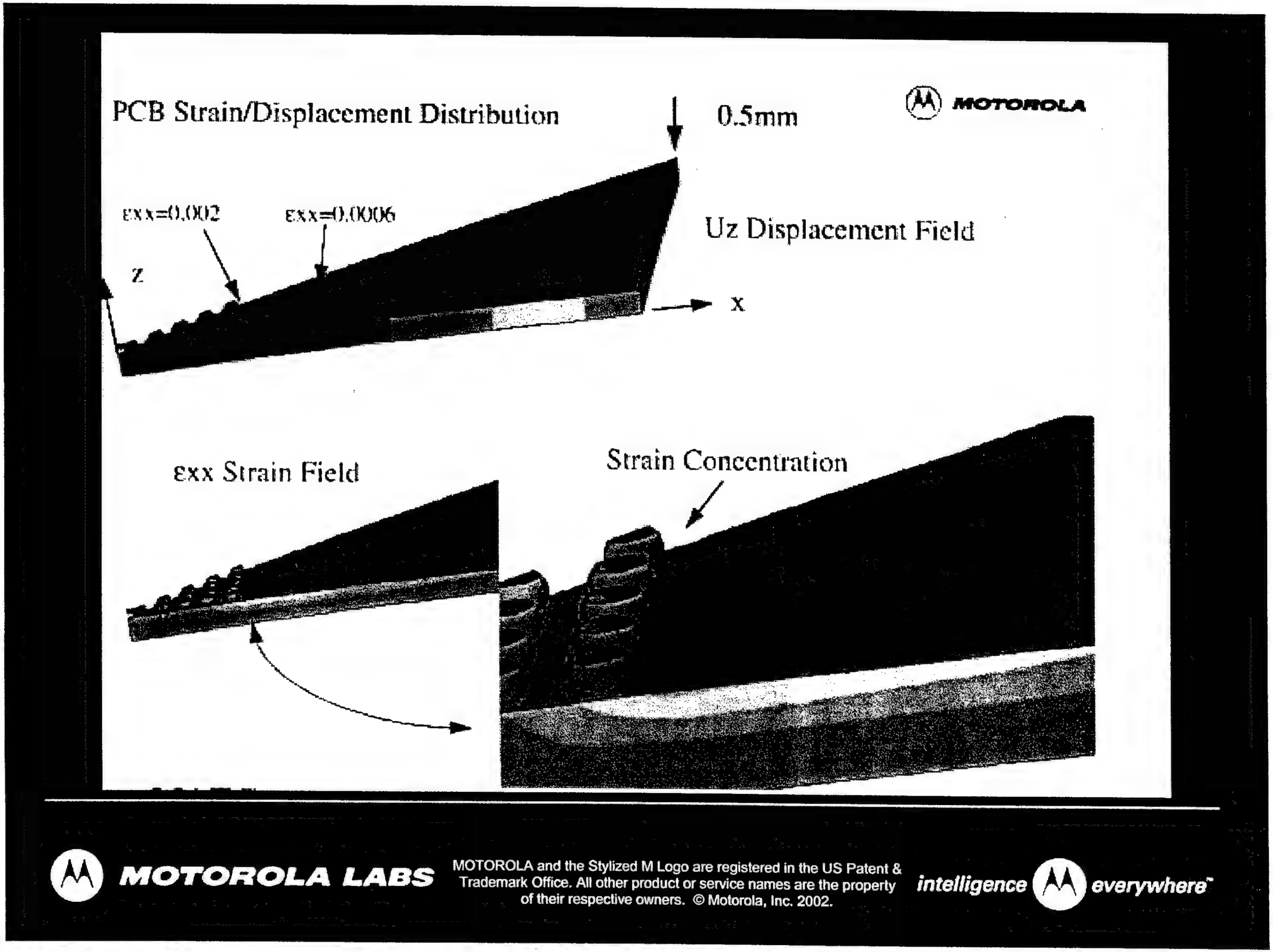
intelligence everywhere

Finite element model results: PCB strain concentration and distribution



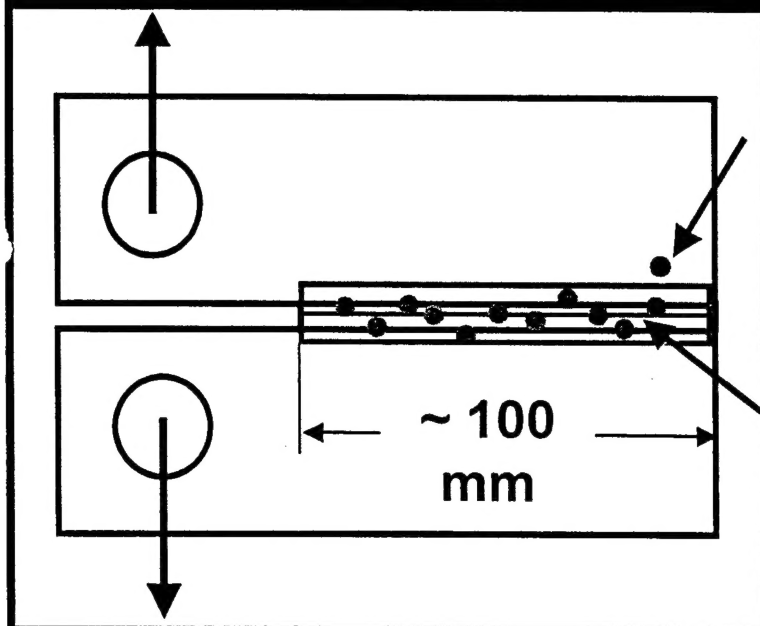
MOTOROLA LABS

intelligence everywhere


PCB Strain/Displacement Distribution
0.5mm
MOTOROLA
εxx=0.002
εxx=0.0006
Uz Displacement Field
z
x
εxx Strain Field
Strain Concentration
MOTOROLA LABS
MOTOROLA and the Stylized M Logo are registered in the US Patent & Trademark Office. All other product or service names are the property of their respective owners. © Motorola, Inc. 2002.
intelligence everywhere™

Near Term Challenges

Compact Tension Specimen

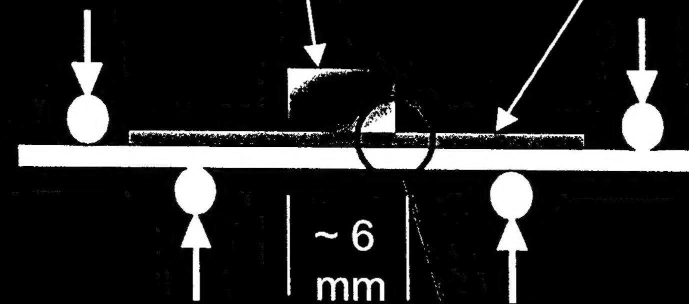


Self heal Opportunities (not to scale)

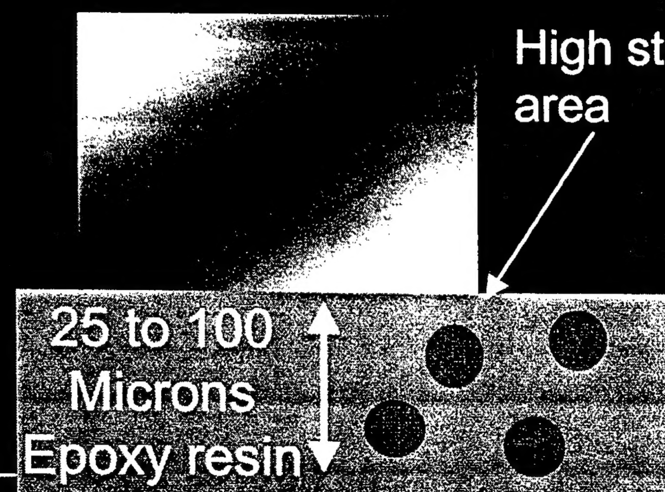
Controlled fracture path

Model microelectronic package, “stress concentration.”

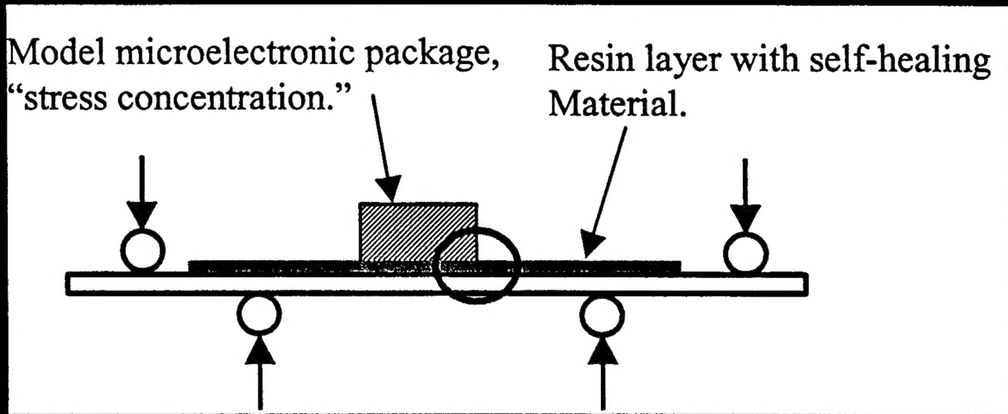
Resin layer with self-healing material.



High stress area



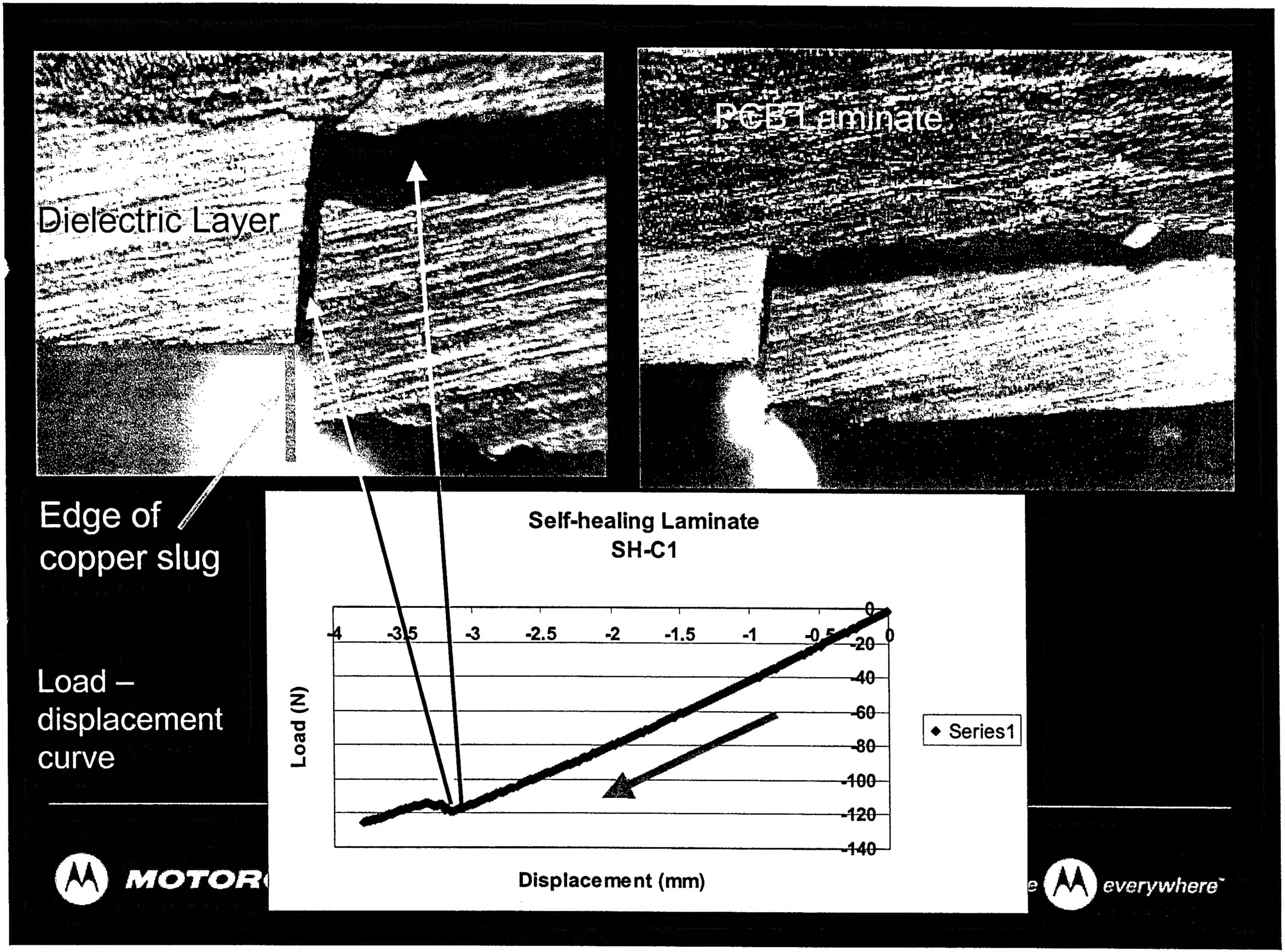
Transition to PCB Laminate
Several self-heal opportunities
vs.
much smaller population.



Examples of test specimen fracture

MOTOROLA LABS

intelligence everywhere™



Dielectric Layer
PCB Laminate
Edge of copper slug
Load – displacement curve
Self-healing Laminate
SH-C1
Load (N)
Displacement (mm)
Series1
MOTOR
everywhere

Future Considerations

- Challenge : Transition concepts to PCB Laminate

- Potential requirements:
    - Room temperature self-heal process
    - Can it work at – 40 C to 125 C ?
    - Non-invasive
    - No premature activation

Electronic Assembly Processing

❖ Tolerate product operating temperatures (– 40 C to 125 C)

❖ Tolerate component/PCB solder assembly processing temperatures (~ 240 C for 15 seconds)

Can the PCB be recycled ?